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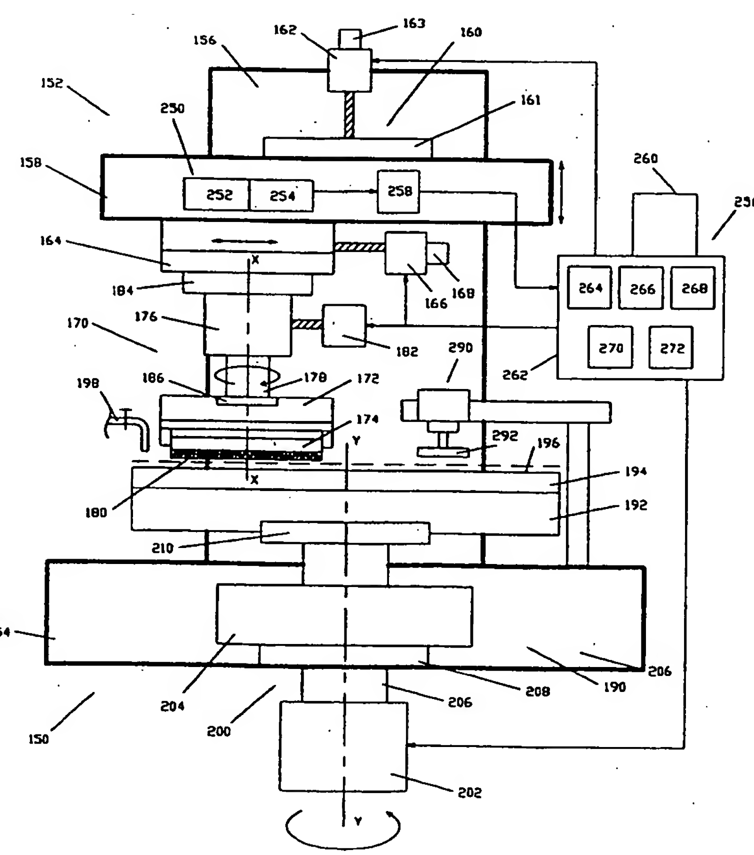
(54) Title: A METHOD AND APPARATUS FOR CONTROLLED POLISHING



(57) Abstract: An apparatus (150) for controlling a polishing process, in particularly for detecting an end point of a wafer (174), comprising a moving platen (192) with a pad (194), a rotating head (170) that supports the wafer and perfoms radial movements with respect to the platen, and a process control system (256) comprising at least two groups of various sensing devices for detecting changes of the processing parameters. The sensing devices include electrical elements connected via contacts embedded in the platen to respective electrical measurement unit, high-frequency acousting sensors (280) built into components of the rotating head and/or polishing pad, mechanical force and torque sensors that may be connected with drive shafts of the rotating head and the platen. Two of these three groups of sensors work simultaneously, and their measurement data are processed and analyzed together by a processing and control units for obtaining accurate and reliable results.

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A METHOD AND APPARATUS FOR CONTROLLED POLISHING

Field of the Invention

The present invention relates to the field of polishing, in particular to the field of chemical mechanical polishing. More particularly, the invention relates to methods and apparatus for controlling and optimizing chemical mechanical polishing processes used in the manufacture of semiconductor wafers and integrated circuits.

Background of the Invention

Polishing is a technological process widely used in a semiconductor industry for manufacturing, e.g., semiconductor wafers with surfaces of high planarity. Planarized surfaces are highly desirable on shallow trench isolation layers, inter-layer dielectrics, inter-metal dielectrics, and other layers used in modern microelectronics. The polishing planarization process is important since, in order to fabricate the next level circuit, high-resolution lithographic and similar processes must be utilized. The accuracy of the high-resolution processes can only be obtained when they are carried out on a substantially flat surface. The planarization process is therefore a crucial processing step in the fabrication of a semiconductor device.

A planarization process can be carried out by chemical-mechanical polishing, or CMP. The process has been widely used in fabricating semiconductor devices of various types. A wafer is frequently planarized several times during a fabrication process in order for the top surface of the wafer to be as flat as possible.

A CMP process can be performed, e.g. by using a moving polishing platen with a polishing pad in combination with a moving polishing head, holding the wafer. A wafer can be polished in a CMP apparatus by being placed on a carrier, assembled on the rotating head, and pressed down, under controlled pressures, onto a polishing pad, which is attached on the platen and covered with a polishing slurry, e.g. of colloidal silica or alumina. A polishing pad may have an either rotational or orbital or linear motion, with the rotation being the most widely used in the industry. The wafer is also rotated during the polishing process to prevent a tapered profile of its surface. The axes of rotation of the wafer and pad are not collinear, though parallel.

Both the CMP and traditional mechanical abrasion polishing processes have a difficulty of their process control. In particular, end point detection, or exact determination of a moment at which the polishing process has to be stopped, has been a problem for the industry. The CMP process is frequently carried out without a clear signal about when the process is completed, just by using only empirical polishing rates and timed polish instead. Since the calculation of required polish time based on empirical polishing rates is frequently inaccurate, the empirical method fails frequently, resulting in serious yield drops and waste of the expensive wafers with devices.

Therefore, process control and end point detection are the important issues for automation of the aforementioned processes.

Known in the art are process control methods utilizing either optical or acoustical or electrical or mechanical measurements.

Optical methods are based on surface reflectivity, light transmission, and interferometry measurements, e.g., by means of a laser beam. An example of such method is described by Koos et.al., in U.S. Pat. No. 5,413,941. Here the wafer being polished is faced against a mirror as it comes off-platen. Laser light is passed transversely between the wafer surface and the mirror, causing multiple reflections between mirror and wafer. A detector at the opposite side records the linear intensity signature of the wafer surface from the exit beam. Optical methods, however, may not be effective in chemical mechanical polishing involving the use of nontransparent media such as polishing slurry.

Another group of methods and apparatus for end-point detection during CMP is based on the measurements of sound waves or acoustic noise, generated in the interface between the wafer and polishing material, and detected with a microphone (e.g., U.S. Pat. Nos. 5,439,551, 5,222,329) or an acoustic sensor (AE sensor). In the context of our invention term "acoustic sensor" means any sensor that detects contact acoustic emission signals (AE signals) or mechanical waves (vibrations) and converts them into electric signals, or acoustic data signals. These methods and apparatuses are based on the fact that when one layer is removed and the next layer is exposed by CMP, this transition is characterized by noticeable changes in the amplitude and spectrum of an acoustic signal. They use AE sensors outside of the polishing zone and separated from the signal source by an air gap, so their recorded acoustic signal has a low level and contains a lot of environmental noise, especially when there is no signal filtering done to filter out the noise. Therefore a signal-to-noise ratio is very low, which reduces the accuracy of process control.

US Patent No. 5,876,265 issued on March 2, 1999 to T. Kojima describes a polishing apparatus with end point detection based on analysis of acoustic signals. The apparatus includes a vibration detecting device attached to the wafer carrier, an amplifier, a gain indicator with gain adjuster to adjust a gain of such amplifier, an end-point analyzer based on the change in said adjusted signal, and a controller. This patent, however, covers only low-frequency signals, which makes it less sensitive to changes in the polishing process, and also does not allow make a distinction between regular acoustic signals and those generated due to abnormal polishing conditions, such as delaminations and scratches.

US Patent No. 5,245,794 issued on 09.21.93 to I. Salugsugan describes a CMP control system, which includes a transducer for converting the acoustic wave energy in the range of 30 to 100 Hertz into an audio signal. The filtered audio signal is supplied to a phase lock loop to detect a predetermined audio frequency and, in response, provide a logic signal to an integrator. The integrator supplies a detection signal, which starts a counter to provide a predetermined over-polishing time prior to termination of polishing. Another method and apparatus for end-point detection during CMP are based on the measurements and analysis of low-frequency vibrations (typically, less than 50 kHz), caused by interactions of the polishing pad and semiconductor wafer in the course of polishing (e.g., U.S. Patent No. 5,876,265).

Both these acoustic methods and apparatuses use relatively low-frequency measurements and thus do not provide high accuracy and resolution in micro-scale process detection required for thin-film polishing and planarization. Also, there is significant influence of environmental noise and vibrations having similar bandwidth. Also, the known acoustic methods do not give

quantitative evaluation of changes in a polishing process, they just only establish the fact of occurrence of the changes and do not distinctly distinguish between regular peaks of signals and extraordinary peaks.

The CMP processes typically involve polishing of one external layer on the wafer surface till the next layer is exposed. Usually these layers comprise various materials with different electrical characteristics, like electrical conductivity, dielectric constant, etc. So, measurements of these characteristics may be used for end point detection.

An example of an electrical method for control of polishing is described in U.S. Patent No. 6,015,754. Implementation of this method requires electrical contacts to be provided to the wafer surface at certain locations and a special test pattern to be created on the surface before processing, which complicates the process and is impractical. Another method and apparatus per U.S. Patent No. 5,242,524 is based on the measurements of electrical resistance of the wafer structure. It includes a pair of electrical contacts that connect the surface of a material being polished to the measurement circuitry. Similarly, in U.S. Patent No. 5,337,015 they measure electrical capacitance of the wafer structure with a dielectric layer.

A disadvantage of the known electric methods for controlling polishing consists in that they are applicable only to certain specific conditions of polishing and have a limited application, if any, under other conditions. Other disadvantages are lack of uniformity of CMP control and the fact that they cannot detect micro-scratches and delaminations.

Mechanical methods are based mainly on friction control. Examples of CMP process control based on measurements of the running motor current and detecting the variations of the motor torque, related to the variations of mechanical parameters in the polishing zone, are described, e.g., in U.S. Patents No-s. 5,948,706, 5,830,041, and 5,308,436. Another example, per U.S. Patent No. 5,738,562, is based on the measurements of the variations of translational (lateral) motion of the polishing platen, related to the variations of the friction coefficient of different film materials. Both these methods are based on indirect measurement techniques, used for very approximate evaluation of the friction variations, cannot produce accurate measurements of the friction coefficient and thus, are not used for the practical CMP process control.

U.S. Patent No. 5,948,205, issued to Kodera et al., discloses means for measuring friction between the layer being polished and a turntable carrying a polishing slurry, determining the rate of polishing the layer based on the measured friction, and determining the extent of polishing of the layer by integrating the polishing rate over time. This apparatus measures distortion of the shaft connected to the polishing turntable to determine the friction.

WO Patent No. 01/15865 A1, published on March 8, 2001 by Moore, describes an apparatus and a method for conditioning and monitoring media used for CMP, with a force sensor connected to the conditioning body support measuring a friction force between the conditioning body and a polishing pad.

However, as has been stated above and is shown in the aforementioned patent, the frictional force can be a function of the surface characteristics of the pad and/or of the conditioning tool, as well as a function of the normal compression force and the relative velocity between the two surfaces. Therefore, a demand for more accurate control of the pad conditioning still exists.

Thus, the known methods and apparatus based on measurement of friction do not provide full control and measurement of real friction characteristics inherent in a CMP process. Therefore, the prior-art technique based on measurement of friction is not suitable for complete control and

optimization of the CMP process and for selection of most optimal pairs of materials for friction under specific operation conditions.

Objects of the Invention

It is an object of the present invention to provide effective, universal, accurate, and reliable method and apparatus for controlling CMP processes. Another object is to provide a method and apparatus that control CMP processes on the basis of combined direct mechanical, electrical, and acoustical measurements of polishing conditions. Still another object is to provide method and apparatus which equally applicable for controlling CMP in treating both layered and uniform materials of various types. It is another object to provide a method and apparatus for directly measuring a friction coefficient in a CMP process under various operation conditions and with the use of different polishing materials. Yet another object is to provide an apparatus and method for a CMP process with controlled conditioning of the polishing pad surface. A further object of the invention is to provide a method and apparatus for polishing control with quantitative evaluation of changes in the polishing process. Another object is to provide a method and apparatus for automatic analysis of acoustic signals and for controlling the process in a manner that allows to optimize polishing conditions and thus to prevent occurrence of defects during polishing. Another object is to provide a method and apparatus capable of separating the extraordinary signal peaks from regular signal peaks.

Summary of the Invention

An apparatus for controlling a polishing process, such as a CMP process, in particular for detecting an end point in polishing layers of a semiconductor wafer, comprising a moving platen with a pad, a rotating head that supports, e.g., a semiconductor wafer and performs radial movements with respect to the platen, and a process control system comprising a plurality of at least two groups of various sensing devices for detecting changes of the process parameters. One group of the sensing devices is a group of electrical elements formed in the pad and connected via contacts embedded in the body of the platen to respective electrical measurement unit. Another group of sensing devices is represented by high-frequency acoustic sensors built on various levels into components of the rotating head and/or polishing pad. Still another group of sensing devices is represented by mechanical force and torque sensors that may be connected, e.g., with drive shafts of the rotating head and the platen, and intended for direct measurement of a coefficient of friction between the wafer and the polishing pad. At least two of these three groups of sensors work simultaneously, and their measurement data are processed and analyzed together by a data acquisition, processing and control units for obtaining accurate and reliable results. In accordance with one embodiment of the invention, the apparatus measures friction and compression forces simultaneously with high-frequency acoustic emission signals corresponding to changes that occur in the interface between the object and the pad. The analysis of these signals, in particular peaks of AE signals, allows to control a polishing process more effectively and accurately and to obtain better polishing results. Another embodiment includes a pad conditioner equipped with the force sensors, the control unit receives the data signals, computes parameters of conditioning, and controls polishing process for obtaining repeatable and accurate results.

In another embodiment of the invention, the control and monitoring system contains a signal conditioning unit for processing operating data signals generated by the sensors and a control unit for generating a control signal for controlling the drives of the polishing tool. The signal conditioning unit amplifies the operating data signals and sends them to a signal analyzer,

which determines average values and peaks of the conditioned signals. The control and monitoring system determines a ratio of the peak signal values to an average signal values and by comparing the obtained ratio with a known reference value optimized with regard to the specific CMP process carried out on the polishing machine. When the measured signal ratio reflects abnormal conditions, polishing process is adjusted back to normal based on a control signal generated on the basis of the aforementioned ratio. The apparatus of the invention also provides quantitative evaluation of changes in the CMP process and automatic control of the CMP process in a manner that optimizes the process and prevents occurrence of defects that might be caused by polishing.

Brief Description of the Drawings

FIG. 1 is a schematic vertical partially sectional view of the apparatus of the invention.

FIG. 2 is a plan view of the platen with the pad.

FIGS. 3A, 3B, 3C, and 3D are graphs illustrating changes in time for electrical resistance, capacitance, torque/friction, and acoustic emission signals respectively, the changes being measured during polishing for the case of a semiconductor wafer with a conductive external layer and a dielectric next layer.

FIGS. 4A, 4B, 4C, and 4D are graphs illustrating changes in time for electrical resistance, capacitance, torque/friction, and acoustic emission signals respectively, the changes being measured during polishing for the case of a semiconductor wafer with a dielectric external layer and a conductive next layer.

FIG. 5 is a schematic front view of the apparatus of the invention.

FIG. 6 is a view similar to FIG. 5 with more detailed illustration of the polishing head.

FIG. 7 is a graph of a friction coefficient versus polishing time for a three-layer structure processed in the apparatus of the invention.

Fig. 8 is a graph of a friction coefficient versus polishing time for a two-layer structure processed in the apparatus of the invention.

FIG. 9 illustrates variations in a coefficient of friction COF between a workpiece and the pad; the same graph shows a curve of a high-frequency acoustic emission (AE) signal versus time in polishing a semiconductor wafer with multiple layers of different materials on the front surface.

FIG. 10 shows experimental graphs of the friction coefficients and high-frequency acoustic emission signals during the polishing of a multi-layered semiconductor wafer with low adhesion of the second layer to the substrate.

FIG. 11 is an embodiment of the polishing head with a plurality of groups of high-frequency acoustic emission sensors embedded into the retaining ring, mounted on the backing plate 276, and embedded into the object holder.

FIG. 12 is an embodiment of the polishing apparatus with a conditioning unit mounted on a movable arm and capable of moving along the pad surface.

FIG. 13 is a general schematic view of the apparatus according to another embodiment of the invention.

FIG. 14 is an example of registration of AE signals obtained during polishing of a laminated structure consisting of layers I, II, and III of materials with different physical properties.

FIG. 15 is a graph illustrating occurrence of AE signals with high average value but without noticeable peaks.

Fig. 16 is a graph similar to the one in Fig. 15, but with the peaks lower than the average level of the acoustic signals shown in Fig. 15.

Fig. 17 is a detailed block diagram of the control and monitoring system of the apparatus of the invention shown also in Fig. 13.

Fig. 18 is an example of a comparator suitable for the apparatus of Fig. 17.

DETAILED DESCRIPTION OF THE INVENTION

The inventors have developed a novel method and apparatus for controlling a polishing process, including efficient and accurate end-point, delamination and micro-scratching detection. The invention is based on the principle of detecting changes of multiple physical characteristics on surfaces and inside the object being polished, caused by surface interaction during polishing. These changes are detected and measured by simultaneously utilizing at least two of mechanical, electrical, and acoustical measurements used in various combinations. The results of these specific measurements are then compared and analyzed for use in controlling the polishing process and eliminating its potential abnormalities.

First embodiment of such apparatus is shown in FIG. 1, which is a schematic vertical partially sectional view. The apparatus of this embodiment of the invention has a platen 20 driven into rotation by means of a motor with transmission (not shown) on a shaft 22 around the axis X--X. It shall be noted that though rotation is shown here, other platen motions like orbital or linear are equally possible. The platen 20 supports a polishing pad 24 made, e.g., from a nonconductive elastic polymer. The pad 24 is a consumable part, which wears out during polishing and is replaceable.

A plan view of the platen 20 with the pad 24 is shown in FIG. 2; though a round shape is shown here, it shall be noted that other shapes of both platen and pad are possible, e.g., both the platen and the pad may have a form of an endless belt. The pad 24 may contain a plurality of groups, e.g., M groups, of conductive pins 26A, 26B, . . . 26M, embedded into the body of the pad and exposed to its working surface S, and electric contacts 27A, 27B, . . . 27M (described below) in the body of the platen. In the illustrated example, each group 26 of pins consists of four conductive pins. More specifically, a group 26A has conductive pins 26A-1, 26A-2, 26A-3, and 26A-4. A group 26B has conductive pins 26B-1, 26B-2, 26B-3, 26B-4 . . . A group 26M has conductive pins 26M-1, 26M-2, 26M-3, 26M-4. These conductive pins can be formed, e.g., by forming through holes in the pad 24 and filling these holes with a conductive elastomer, so that the pins, which are exposed to the upper and lower surfaces of the pad 24, can be deformed together with the resilient pad 24. The groups of pins are circumferentially equally spaced from each other on circles which are concentric with respect to the shaft 22. Two such concentric circles are shown in FIG. 2, though the number of circles may also be one or more than two. The platen 20 has groups 27 of contacts 27A-1, 27A-2, 27A-3, 27A-4 (shown on FIG. 1 only for

the group 27A), etc., which are continuations of the aforementioned conductive pins 26A-1, 26A-2, 26A-3, 26A-4, 26B-1, 26B-2, 26B-3, 26B-4,. . . 26M-1, 26M-2, 26M-3, 26M-4 of the pad 24 and therefore are arranged in the same pattern, so that replacement of the pad will not discontinue respective electric circuits. The groups of contacts 27A-1, 27A-2, 27A-3, 27A-4, . . . 27M-1, 27M-2, 27M-3, 27M-4 together with conductive pins 26A-1, 26A-2, 26A-3, 26A-4, . . . 26M-1, 26M-2, 26M-3, 26M-4 form corresponding electrical resistance probes 28A, . . . 28M.

If the platen 20 is made of an electrically conductive material, such as metal, the aforementioned contacts are electrically isolated from the body of the platen 20 by an insulating material 29 (FIG. 1). The conductive pins 26A-1, 26A-2, 26A-3, 26A-4, . . . 26M-1, 26M-2, 26M-3, 26M-4 are electrically connected via the contacts 27A-1, 27A-2, 27A-3, 27A-4, etc. and conductive wires, such as wires 30A-1, 30A-2, 30A-3, 30A-4, shown on FIG. 1 only for the group 26A of the conductive pins, to a resistance measurement unit 32 which is attached, e.g., to the bottom side of the platen 20 and rotates therewith.

The resistance measurement unit 32 contains, for example, an AC or DC current source 38, a voltage drop signal conditioner 40, and commutation circuitry 42 with a position detection device 44, that provides synchronous commutation of conductive pins 26A-1, 26A-2, 26A-3, 26A-4, 26B-1, 26B-2, 26B-3, 26B-4, . . . 26M-1, 26M-2, 26M-3, 26M-4 to a connecting unit 46, which consists of a moveable part 46a that rotates together with the platen assembly and a stationary part 46b that is connected to a data processing and control system 47. This data processing and control system processes received data signals and sends control commands to the motion control units for both head and platen motors (not shown). During operation of the apparatus, each group of contacts is sequentially connected to the resistance measurement unit 32 so that the respective conductive pins 26A-1, 26A-4, 26B-1, 26B-4, . . . 26M-1, 26M-4 are connected to the current source 38, whereas the remaining conductive pins 26A-2, 26A-3, 26B-2, 26B-3, . . . 26M-2, 26M-3 are connected to inputs of the voltage drop signal conditioner 40.

The apparatus of the invention also has a plurality of groups, e.g., N groups, of conductive elements 48A, 48B, ...48N (FIG. 2) such as 48A-1, 48A-2; 48B-1, 48B-2; . . . 48N-1, 48N-2, embedded within the material of the pad 24 and made, e.g., from an electrically conductive elastomer. Similarly dimensioned and arranged groups of contacts 49A-1, 49A-2, etc., which are circuit continuations of the pad's conductive elements 48A-1, 48A-2; etc., are formed in the body of the platen 20 and are isolated therefrom by insulating material 50, if the platen 20 is made of an electrically conductive material. In the illustrated example, each group of conductive elements and contacts consists of two concentric conductive elements and contacts. These groups of conductive elements and contacts form a plurality of capacitance probes 52A, 52B, . . . 52N and are also equally spaced in circumferential direction and are arranged on concentric circles. Two circular rows of paired conductive elements are shown in FIG. 2 for illustrative purposes. Each group of conductive elements 48A, 48B . . . 48N consists of an outer or surrounding element, such as conductive elements 48A-2, 48B-2, . . . 48N-2, and an inner conductive elements, such as 48A-1, 48B-1, . . . 48N-1. Similarly, each group of contacts 49A, 49B . . . 49N consists of an outer or surrounding contact, such as contacts 49A-2, 49B-2, . . . 49N-2, and an inner contact, such as 49A-1, 49B-1, . . . 49N-1. Each aforementioned capacitance probe 52A, 52B, . . . 52N is electrically connected by respective conductive wires 54A-1, 54A-2, etc. (FIG. 1), to a capacitance measurement unit 56. The capacitance measurement unit 56 is attached to the platen 20 and contains, e.g., a high frequency low voltage signal generator 58, a voltage follower 60, an amplitude control circuitry 62, a current-to-voltage converter 64, an output signal conditioner 66, and a commutation circuitry 68 with a position detection device (not shown) for providing synchronous commutation of groups of conductive elements 48A-1, 48A-2, 48B-1, 48B-2, . . . 48N-1, 48N-2 to the connecting unit 46. During rotation of the platen 20, each capacitance probe 52A, 52B . . . 52N is sequentially

connected to the capacitance measurement unit 56.

The apparatus of the invention further may contain a first mechanical sensing unit 70 (FIG. 1), which may comprise a torque sensor, a force sensor or a multi-axis force/torque sensor. An example of such a sensor is a force sensor disclosed in our pending U.S. Patent application Ser. No. 09/624,512 filed on Jul. 24, 2000. The mechanical sensing unit 70 is mounted under the platen 20, e.g., on the shaft 22 and measures a compression force applied to the shaft 22 from the side of the platen 20 and/or a rotational torque applied to the platen 20 from the side of the shaft 22. The first mechanical sensing unit 70 is connected to a mechanical measurement unit 72, which is mounted, e.g., under the platen 20 and provides amplification and conditioning of a data signal from the mechanical sensing unit 70.

Output signals from the electrical resistance measurement unit 32, capacitance measurement unit 56, and from the mechanical measurement unit 72 are supplied to the moveable part 46a of the aforementioned connecting unit 46. This unit also contains the stationary part 46b, which is connected to the control and monitoring system 47. The electric connection between the moveable part 46a and the stationary part 46b can be realized via slip-ring contacts, sliding brush-type contacts, or a wireless data transmitting system (not shown).

In the embodiment of FIG. 1, a semiconductor wafer 82 to be polished is held on a rotating head 84 driven by a motor with transmission (not shown) on a shaft 85 around the axis Y--Y, which is parallel but not coaxial to the axis X--X. On its front surface facing the pad 24, the wafer 82 has layers of materials 82a, 82b with different electrical and mechanical properties. The outer layer 82b of the wafer has to be at least partially removed by polishing.

In addition to the rotary movement, the head 84 (with the wafer 82) performs radial movements with respect to the rotating platen 20 (with the pad 24) shown by the arrow K. The apparatus also has a slurry dispensing system 86, which feeds a polishing slurry 88 onto the working surface of the polishing pad 24. In the illustrated embodiment, the rotating head 84 has a housing 90 with a backing plate 92 and/or a wafer holder 94 supporting the wafer 82 from the backside. A retaining ring 96 prevents slippage of the wafer 82 from its place on the head 84 during processing.

The head 84 may have one or several groups of high-frequency AE sensors, chosen from a group of P sensors 98-1, 98-2, . . . 98-P mounted on the retaining ring 96, a group of Q sensors 77-1, 77-2, . . . 77-Q mounted on the backing plate 92, and a group of R sensors 79-1, 79-2, . . . 79-R embedded into the wafer holder 94, respectively. The AE sensors 79-1, 79-2, . . . 79-R are mounted into the wafer holder 94 in such a way, that sensing surfaces of these sensors are leveled in flush with the lower surface of the wafer holder 94 and are to be kept in contact with the backside of the wafer 82 during the processing. The AE sensors can be distributed over the back surface of the supporting plates uniformly, or in any other arrangement pattern. The AE sensors may have a frequency response within the range from 100 kHz up to 10 MHz, preferably 0.5 MHz to 5 MHz, and are connected to an AE measurement unit *81*, which may, e.g., comprise a wide-band amplifier 83, high- or band-pass filter 85, peak detector 87, multiplexer 89, and a signal conditioner 91. The contact AE measurement unit 81 provides amplification of AE signals within a selected frequency band and synchronizes commutation of the signals from multiple AE sensors to the device output. It shall be noted that one or more AE sensors of one or more groups may be used per this invention.

The apparatus of the invention may have a second mechanical sensing unit 97, which may be in the form of a torque sensor, force sensor, or multi-axis force/torque sensor. An example of such a sensor is a force sensor disclosed in our pending U.S. Patent application Ser. No. 09/624,512

filed on Jul. 24, 2000. This sensing unit is mounted above the rotating head 84, e.g., on the shaft 85 and measures a compression force and/or a rotational torque applied to the rotating head 84 from the side of the shaft 85 and/or a tangential friction force applied to the shaft 85 from the side of the rotating head 84. The mechanical sensing unit 97 is connected to a mechanical measurement unit 93, which is mounted, e.g., above the rotating head 84 and provides amplification and conditioning of a data signal from the sensing unit 97.

Output signals from both the AE measurement unit 81 and the mechanical measurement unit 93 are supplied to a connecting unit 95, which consists of a moveable part 95a rotating with the head assembly, and a stationary part 95b connected to the signal control and monitoring system 47. The connection unit 95 is used to transfer electrical signals between the AE emission measurement unit 81, the mechanical measurement unit 93, and the aforementioned control and monitoring system 47. Electric connection between the rotating and stationary parts can be carried out via slip-ring contacts, sliding brush-type contacts, or a wireless data transmitting system (not shown).

The apparatus of the embodiment shown in FIGS. 1 and 2 operates utilizing at least two groups of sensing means as follows.

During a CMP process, each group of conductive pins 26A-1, 26A-2, 26A-3, 26A-4, 26B-1, 26B-2, 26B-3, 26B-4, . . . 26M-1, 26M-2, 26M-3, 26M-4 of the resistance probes 28 passes under the wafer 82. As a result, the electrical current flows through the contacts 27A-1, 27A-4; 27B-1, 27B-4; . . . 27M-1, 27M-4 of the resistance probes 28A, 28B, 28M, which are connected to the current source 38, through the conductive pins 26A-1, 26A-4; 26B-1, 26B-4; . . . 26M-1, 26M-4 of respective group in the pad 24, and through the portion of the wafer surface between corresponding pins 26A-1, 26A-4; 26B-1, 26B-4; . . . 26M-1, 26M-4. The voltage drop is measured between the remaining conductive pins 26A-2, 26A-3, 26B-2, 26B-3, . . . 26M-2, 26M-3, which are connected to inputs of the voltage drop signal conditioner 40. This voltage drop is proportional to the surface resistance of the wafer 82. When the head passes over a specific group of conductive pins of the pad, e.g., the pins 26A-1, 26A-2, 26A-3, and 26A-4, the output voltage drop signal is supplied via the pins 26A-2, 26A-3 to the resistance measurement unit 32, which also contains the synchronization mean that allows to take the measurements only from the group of pins which are currently under the wafer 82.

Similarly, during the CMP process, each group of conductive elements, such as 48A-1, 48A-2; 48B-1, 48B-2; . . . 48N-1, 48N-2, passes under the wafer 82 and connects corresponding contacts of the capacitance probes 52A, 52B, . . . 52N to the wafer surface. As a result, high-frequency electrical current from the signal generator 58 passes through the contacts 49A-1, 49A-2, etc., through the conductive elements 48A-1, 48A-2 etc., and through the surface of the wafer. Then the current, which is proportional to the probe capacitance, passes trough the current-to voltage-converter 64 and the output signal conditioner 66 of the capacitance measurement unit 56. As has been mentioned above, the capacitance measurement unit 56 is equipped with synchronization means that allows taking measurements only from the group of conductive elements that currently passes under the wafer 82.

In addition to the measurements described above, in the course of the CMP process, the signal processing and control system of the apparatus of the invention may constantly measure and register a loading compression force applied to the wafer 82 from the side of the rotating head 84 and the rotational torques applied to the shafts 22 and 85. These measurements are performed by the mechanical sensing units 70 and 97. At a given loading force and a radial position of the head, the aforementioned rotational torques are proportional to a friction coefficient (COF) between the wafer 82 and the polishing pad 24.

The AE sensors 98-1, 98-2, . . . 98-P, 77-1, 77-2, . . . 77-Q, 79-1, 79-2, . . . 79-R mounted on the head in at least one of the following locations: the retaining ring 96, on the backing plate 92, and in the wafer holder 94, detect contact acoustic emission generated in the interface between the wafer 82 and the pad 24 during the CMP process and caused by interaction of the wafer surface with the slurry particles on the pad surface. These acoustic emission waves propagate through the bodies of the wafer 82, the wafer holder 94, the backing plate 92, and the retaining ring 96. Since all the parts conducting these waves (wafer, holder, backing plate, retaining ring) are made of solid materials with good elastic properties, propagation losses of the acoustic signals received by AE sensors in the device of invention are much lower than the losses of signals received by microphones of known CMP control systems where the microphones are separated from the wafer by an air gap. Both amplitude and frequency spectrum of an AE signal depend in large on the mechanical properties of interacting surfaces, and any given combination of materials on the interacting surfaces produces a unique spectrum of acoustic signals. Therefore, monitoring the AE signals from the interface between the wafer and the pad within predetermined frequency band makes it possible to control the polishing process.

It is understood that at any given velocity of interacting surfaces, the time of interaction between small features on these surfaces is proportional to the dimensions of these features, and that the smaller surface features have to be detected, the shorter response time of a detecting system is required. At a typical rotational speed of 60 rpm, which corresponds to linear speeds of the order of 1 m/s, and with modem semiconductor wafers having sub-micron surface features, the response time of a detecting system has to be within sub-microsecond range. Therefore in order to detect micro-processes in the wafer-pad interface during the CMP, AE sensors with high bandwidth of several megahertz shall be used.

Let us assume that the outer layer 82b is made of metal, the next layer 82a is made of dielectric, and that the material of the pad 24 has a lower coefficient of friction against the material of the outer layer 82b than against the material of the next layer 82a.

The CMP process is continued until the upper conductive layer is removed. When this layer is removed, the electrical resistance of the layered structure increases, and the corresponding voltage drop measured on the portion of the wafer surface between conductive pins 26A-2 and 26A-3 increases. The output signal from the resistance measurement unit 32 received by the control and monitoring system 47 rises, which reflects the fact that the end point of CMP has been reached. This condition is shown in FIG. 3, where changes in time for electrical resistance is shown in FIG. 3A, for capacitance probes in FIG. 3B, for coefficient of friction and torque in FIG. 3C, and for AE in FIG. 3D.

Simultaneously, a high-frequency electrical current from the signal generator and, respectively, an output signal of the capacitance measurement unit 56 drops from the high level, corresponding to full contact between conductive elements of the current capacitive probe through the metal layer 82b (short circuit), down to the low level, corresponding to thickness of the dielectric layer 82a, that also testifies to the fact that the end point of CMP has been reached (see FIG. 3B). Further continuation of the polishing process beyond this point would cause an increase in the output signal of the capacitance measurement unit 56, corresponding to the dielectric layer thickness reduction.

At the same time, the coefficient of friction between wafer and polishing pad and, respectively, output signals from at least one of the mechanical sensing unit 70 and the mechanical sensing unit 97 change from the low level, corresponding to the interactions between the pad 24 and the material of the layer 82b, to the high level, corresponding to the interactions between the pad 24

and the material of the layer 82a (see FIG. 3C).

As described above, mechanical properties of interacting surfaces define the amplitude and frequency spectrum of the AE signal. Therefore, after removal of the upper layer 82b from the wafer, the output signal from the acoustic emission measurement unit 81 changes its level according to the change in the properties of the wafer surface layer 82a. This testifies to the fact that the end point in CMP is reached (see FIG. 3D). The final stage of polishing of the layer 82b can be characterized by irregular variations in the AE signal (e.g., in the form of peaks and jumps), which can be used as a precursor of the end point (FIG. 3D).

Since the AE sensors are used in a number of groups and in different parts of the head over the wafer, their signals can be used for evaluating uniformity of treatment.

Let us assume an opposite configuration, namely, when the outer layer 82b of the wafer is dielectric and next layer 82a is conductive. In this case the layered structure initially has a high surface resistance, which drops when the conductive layer starts to be exposed.

As a result, corresponding voltage drop measured on a portion of the wafer surface between conductive pins 26A-2 and 26A-3 decreases. The output signal from the resistance measurement unit 32 received by the control and monitoring system 47 also changes from a high level in the beginning of the process to the low level (close to zero) indicating that the end point of CMP has been reached. This condition is shown in FIG. 4A. FIGS. 4B, 4C, and 4D show changes in time for electrical capacitance, torque and coefficient of friction, and an AE signal, respectively.

Simultaneously, a high-frequency electrical current from the signal generator and, respectively, an output signal of the capacitance measurement unit 56 increases, corresponding to the dielectric layer thickness reduction. In this case the current is inversely proportional to the thickness of the dielectric layer. When the dielectric layer 82b is completely removed, the conductive elements 48B-1 and 48B-2 come into contact with the metal layer 82a, so that the value of capacitance measured by the capacitance probes 52A, 52B, . . . 52N and the corresponding output signal of the capacitance measurement unit 56 jumps up. This can also be used for the end point detection and control of CMP process (see FIG. 4B).

At the same time, the coefficient of friction between the wafer 82 and the polishing pad 24 and, respectively, the output signals from the mechanical sensing unit 70 and the mechanical sensing unit 97 change from the high level, corresponding to the interactions between the pad 24 and the material of the layer 82b, to the low level, corresponding to the interactions between the pad 24 and the material of the layer 82a (see FIG. 4C). Measurement of coefficient of friction with the use of mechanical sensing units 70 and 97 produces integrated, average parameters of the CMP process over the entire contact area. The changes in AE signal are similar to those described above. After removal of the upper layer 82b from the wafer 82, the output signal from the acoustic emission measurement unit 81 changes, in response to changes in surface properties of the wafer 82, from a high level to a low level, with possible irregularities preceding the transition to the next layer (see FIG. 4D).

Since conductive pins and elements of the pad 24 are used in a plurality of groups, continuous monitoring of the measurement data relating to resistance and capacitance provides high resolution in detecting the end point of the polishing process and allows for measurement with resolution of a fraction of one revolution of the pad 24. Arrangement of the resistance and capacitance probes on various radii of the polishing pad 24 makes it possible to evaluate radial uniformity of material removal from the surface of the wafer.

Thus it has been shown that the present invention provides effective, universal, accurate, and reliable method and apparatus for controlling polishing processes.

The apparatus of the invention controls polishing, e.g., CMP processes on the basis of combined at least two real-time direct mechanical, electrical, and acoustical measurements of polishing conditions. The method and apparatus are equally applicable for controlling CMP in treating both layered and uniform materials of various types.

Another embodiment of this invention includes simultaneous real-time measurements of two parameters during polishing, the polishing coefficient of friction and contact acoustic emission. The applicants have found that control and optimization of polishing based only on friction force or friction torque measurements are not accurate enough to satisfy requirements of modern semiconductor fabrication. A much more important parameter, characterizing properties of contacting materials and degree of their interaction, is a coefficient of friction (COF), which is a ratio of a friction force between two surfaces to a force compressing these surfaces in perpendicular direction. COF can be used as a major parameter in simulation and optimization of a polishing process. Significant variations in a friction force between a wafer and polishing pad can be related to changes in friction properties of both the wafer and the pad, as well as to variations in the normal force that compresses these two parts. During this polishing process, the normal force may also oscillate, e.g., due to runout or non-flatness of a pad, or instability of a loading mechanism, while the friction coefficient may remain constant. While measuring the friction force alone, without the normal compression force, one may come to a false conclusion that during polishing friction properties of the materials participating in friction engagement vary, which is not true.

Another example of usefulness of the friction coefficient measurements is behavior of COF during polishing of the wafer with two layers of different materials on the surface. Each of these two materials (1) and (2) has a specific value for the coefficient of friction against the pad, namely COF1 and COF2. In the beginning of the polishing process, when the uppermost layer on the wafer consists of material (1), the friction coefficient measured in the course of polishing equals COF1. Since during the polishing the outer layer is gradually removed, there is a moment of time (T1) when underlying layer of material (2) starts to be partially exposed, and at a moment T2 the first layer is removed completely, the whole wafer surface is covered with material (2), and the friction coefficient in this system becomes equal COF2. By registering the time moments T1 and T2, one can make a judgment about such characteristics as the material removal rate, uniformity of the material removal over the wafer surface and use this information to determine an end point of the process.

A polishing apparatus of the second embodiment of this invention is shown schematically in Fig. 5, which is its front view. The polishing apparatus, which in general is designated by reference numeral 150, has a frame 152 consisting of a base plate 154, a vertical column 156, and a cross bar 158. The vertical column 156 supports a vertical positioning mechanism 160, e.g., a carriage 161 with a lead screw and a nut (not shown), which is connected to the cross bar 158, can move in vertical direction and is driven by a first drive mechanism1 62, e.g., by a reversible electric motor coupled with the aforementioned lead screw. A first position detector 163 is mechanically coupled with the first drive mechanism 162 and generates a vertical position data signal. The vertical positioning mechanism 160 supports a horizontal positioning mechanism 164, which is also attached to the cross bar 158 and is capable to move in a direction parallel to the base plate 154, either linearly or rotationally around the vertical column, by means of a second drive mechanism 166. A second position detector 168 is mechanically coupled with the second drive mechanism and generates a lateral position data signal.

A head assembly, which in general is designated by reference numeral 170, is mounted on the horizontal positioning mechanism 164 and can rotate around a vertical axis X-X. It can also move along with the horizontal positioning mechanism 164 in a horizontal direction parallel to the base plate 154.

Fig. 6 is a schematic view of the apparatus of the invention with more detailed illustration of the polishing head. As can be seen from this drawing, the head assembly 170 consists of a holding chuck 172 for holding and supporting an object 174 be treated and a rotating unit 176 with a shaft 178. The object, e.g., a semiconductor wafer, has a front surface180, which has to be polished during a polishing. The head assembly 170 is coupled with a third drive mechanism 182, e.g., electric motor, which rotates the head assembly 170 around the axis X-X.

A mechanical sensing assembly 184 mounted on the head assembly 170 is installed between the horizontal positioning mechanism1 64 and the rotating unit 176. The mechanical sensing assembly 184 has means for detecting a compression force F1 acting along the axis X-X in a direction perpendicular to the front surface 80 of the wafer 174. The sensing assembly 184 also has means for detecting a friction force F2 acting in a second direction parallel to the front surface of the wafer and a means for detecting a friction torque T1 acting in respect to the axis X-X. It is understood that the compression force F1 and the friction force F2 occur only when the front surface 180 of the object 174 is in contact with the pad and the friction force F2 occurs only when both parts participate in a relative motion. For convenience of the drawing, however, these forces are conventionally shown on the object when the head assembly 170 is raised over the pad. Symbol T1 designates a friction torque on the head assembly 70.

The polishing apparatus 150 can also be equipped with another mechanical sensing assembly 86 that could be mounted on the head assembly 170 and is provided with means for combined sensing and detecting forces F1, F2 and friction torque T1. In the embodiment illustrated in Fig. 6, the second sensor assembly 186 is installed between the shaft 178 and the holding chuck 172.

The base plate 154 of the tester frame 152 supports a polishing module 190 (Fig. 6), which has a platen 192 with a polishing pad 194. The polishing pad 194 is attached to the platen 192 so that it can be removed and replaced, e.g., by means of adhesive film (not shown). The uppermost surface 196 of the pad facing the object, e.g., a semiconductor wafer, is a working surface of the pad. During polishing, this surface is in contact with the front surface 180 of the wafer and carries a polishing slurry delivered by a slurry feeding system 198 (Fig. 5). The polishing module 190 also contains a polishing drive mechanism 200, which is used for moving the platen 192 with the pad 194 relative to the semiconductor wafer 714. The polishing drive mechanism 200 consists of a polishing drive motor 202 and a transmission unit 204 with a drive shaft 206, that connects the polishing drive motor 202 with the platen 192. The transmission unit can be selected from a rotary type transmission, which transmits rotation from the polishing drive motor to a polishing platen 192, an orbital type transmission, which transforms rotation of the polishing drive motor 202 into orbital motion of the platen 192, and a linear transmission (not shown). The transmission unit 204 is connected to the base plate 154 of the frame 152 via a third sensor assembly 108 having sensors for combined sensing and detecting forces F1, F2, and friction torque T2 developed during rotation of the platen 192 around the axis Y-Y, which passes through the center of the platen.

A fourth sensor assembly 110 having sensors for combined sensing and detecting forces F1, F2, and friction torque T2 can be mounted on the platen 192 and attached to the drive shaft 206 of the transmission unit 104 and to the platen 192.

During polishing, the front surface 180 of the semiconductor wafer 174 is brought into contact with the working surface 196 of the polishing pad 194 mounted on the platen 192, and a compression force F1 acting in a direction perpendicular to the front surface of the wafer and to the working surface of the pad 194 is applied by feeding the vertical positioning mechanism 160 downward in a vertical direction (Figs. 5 and 6). The head assembly 170 supporting the wafer rotates around the axis X-X and at the same time performs radial motions relative to the center of the platen 192. These radial motions are caused by the horizontal positioning mechanism 164, while the platen 192 rotates in respect to the axis Y-Y or performs orbital motions. Motions of the platen 192 with the pad 196 relative to the semiconductor wafer 174 causes a friction force F2 acting in a direction parallel to the front surface of the object and to the working surface of the pad 196, a friction torque (moment of forces) T1 developed around the axis X-X of the head assembly 170, and a friction torque T2 developed around the axis Y-Y of the platen 192.

Mechanical sensing assemblies 184, 186, 208, 210 comprise plurality of sensor elements which can be made in the form of a force sensor detecting a force acting in a direction perpendicular to the working surface 196 of the pad 194 and to the front surface 180 of the object 174 (hereinafter referred to as a first force sensor), a force sensor detecting a force acting in a direction parallel to the working surface 196 of the pad 194 and to the front surface 180 of the object 174 (hereinafter referred to as a second force sensor), and a torque sensor detecting a torque (moment of forces) acting in respect to an axis parallel to the axis X-X (hereinafter referred to as a third sensor) or to the axis Y-Y (hereinafter referred to as a fourth sensor). Aforementioned sensors detect the compression force and corresponding friction response and generate output data signals as a plurality of compression data signals and friction data signals.

The first force sensor and the second force sensor may be of any suitable type, e.g., as the one described in pending US Patent Application No 09-624512 filed by the same applicants on July 24, 2000. The third sensor and the fourth sensor may be torque sensors, consisting of two disks with a thin-walled cylindrical body sandwiched between them. The thin-walled cylindrical body is made of a spring material and has a shear-sensitive element, e.g., strain gauge, for detecting torsion shear deformation of the cylindrical body due to applied torque (moment of forces) Tz acting in respect to the vertical axis of the sensor.

The apparatus of invention further includes a mechanical signal processing assembly 120 (Fig. 5) connected to the mechanical sensor assemblies 184, 186, 208, 210 and having a compression processing unit 252 and a friction processing unit 254. The compression processing unit 252 acquires output data signals from the first force sensor, the friction processing unit 254 acquires output data signals from the second force sensor and from the torque sensor. Both the signal processing units 252 and 254 may be equipped with electronic amplifiers, buffers and filters (not shown) for amplifying and processing the acquired data signals.

The apparatus of invention is also equipped with a control and monitoring system 156 connected to the via a connecting device 258 (Fig. 5) such as a slip-ring with sliding contacts or a wireless data transfer system. The control system 256 may consist of a display device 260, e.g., an electronic graphic monitor or a numerical display for displaying and monitoring data signals and polishing parameters and a data processing system 262, e.g., computer-based controller. The data processing system 262 includes a data receiving unit 264, e.g., a multi-channel data acquisition board for receiving data signals from the transducer assembly 250, a recording unit 266, e.g., a computer hard disk, memory, or storage system for recording and storing the received data signals, a computing unit (arithmetic module) 268, e.g., a computer CPU or stand-alone logical controller for computing a predetermined set of polishing parameters

based on received data signals, an analyzer 270, e.g., a data analysis software or an algorithm for retrieving and analyzing data signals and polishing parameters and for optimizing polishing parameters according to predetermined optimization criteria, and a control unit 272, e.g. motor controllers for controlling operation of the first drive mechanism 162, the second drive mechanism 166, the third drive mechanism 182, and the polishing drive motor 202.

As has been shown above, the coefficient of friction, which is defined as a ratio of the friction force to a corresponding compression force, is one of the most important parameters characterizing interaction between moving parts and various materials participating in friction contact. Fig. 7 is a graph illustrating variations of the friction coefficient COF between the object and the pad versus time in a course of polishing of a three-layer semiconductor wafer with different materials of the layers. As can be seen from Fig. 7, an initial portion of the graph from 0 to moment T1 on the time scale corresponds to polishing of the uppermost layer with the friction coefficient COF1. After moment T1 a second layer with a higher friction coefficient COF2 starts to be partially exposed, and the measurement of the total friction coefficient having an intermediate value between COF1 and COF2 shows the presence on the front surface of both materials simultaneously. After moment T2, when the first layer is completely removed, a portion of the graph between time marks T2 and T3 on the time scale corresponds to the presence of the second material on the front surface of the wafer. After moment T3 a third layer with the friction coefficient COF3 starts to be partially exposed on the front surface, and after moment T4 the second layer is completely removed and the third layer of material is completely exposed on the front surface of the wafer. Knowing values of the friction coefficient for various combinations of different wafer materials and polishing pads, it becomes possible to effectively control the polishing process, in particular, to discontinue polishing once a predetermined specific value of the friction coefficient is reached.

As can be seen from Fig. 7, all three layers of different materials not only have different average values of the friction coefficients, but also show different behavior in the course of polishing, namely different pattern of variation of the friction coefficient within the same layer. A standard deviation, peak values of data signals and of friction coefficients in selected periods of time can be used as criteria for evaluating the aforementioned variations. The above criteria are recommended, as they themselves are also important parameters of a polishing process.

Fig. 8 is a graph that illustrates variations of the friction coefficient versus polishing time for a wafer having two sequential layers with close average values of friction coefficients COF1 and COF3. In that case, measurements based only on the average values do not allow accurate detecting the point of transition in polishing from one layer to another, and detection of signal peaks and standard deviations would help to more effectively control the polishing process.

The control and monitoring system 256 (Fig. 5) is also electrically connected to the first drive mechanism 162 of the vertical positioning mechanism 160 and has a closed loop control with a feedback from the compression transducing unit 252, i.e. the control unit 272 of the data processing system 262 generates control signals for controlling the first drive mechanism in response to the compression data signal, thus allowing for controlling and maintaining the compression force applied to the wafer in the course of polishing.

Another important characteristic of the polishing process that can be used for effective control of polishing is a high-frequency acoustic emission signal, which represents elastic waves generated in the interface between the wafer and the pad and propagating through contacting parts. The amplitude and frequency spectrum of an acoustic emission signal depends on hardness, density and other mechanical properties of interacting parts and on intensity of the interaction, i.e., polishing. Therefore, an acoustic emission signal also can be used as an

additional factor for identifying materials on the front surface of the wafer and for polishing process monitoring and control. Since generation of elastic waves is associated with interaction between small features on the surface of the interacting parts, the acoustic signal generated during such interaction has a very high frequency.

Fig. 9 illustrates variations in a coefficient of friction COF between the object and the pad. The same graph shows a curve of an AE signal versus time in polishing a semiconductor wafer with multiple layers of different materials on the front surface. As can be seen from Fig.9, the first layer on the front surface of the wafer and the second layer have similar average values of the friction coefficient and similar variations in the friction coefficient. Therefore it would be difficult in that case to distinctly define the moment of transition from the first layer to the second one on the friction measurements alone, and the AE signal will contribute to finding the threshold of the aforementioned transition.

Additionally, high-frequency acoustic emission signal can be used for monitoring localized events in the interface between interacting surfaces, such as single scratches, micro-cracks or local delamination of the surface layers. Fig. 10 shows experimental graphs of the friction coefficients and high-frequency acoustic emission signals during the polishing of a multi-layered semiconductor wafer with low adhesion of the second layer to the substrate. As can be seen from Fig. 10, polishing of the second layer is characterized by random spikes with a low background level of AE signal. A subsequent surface analysis confirmed that the spikes shown in this graph represent local delaminations of the film from the substrate. Therefore, detection of peak values in high-frequency acoustic emission signals in combination with the average level of these signals would provide more effective and accurate polishing control.

High-frequency elastic waves can propagate with minimal losses through contacting solid materials such as metals, ceramics or hard plastics, while having significant losses propagating through air and soft materials like rubber. Therefore it's critical for reliable detection of high-frequency acoustic emission signal to provide a continuous path from a source of the signal to a signal detector, i.e., from the wafer front surface to the high-frequency acoustic emission sensors. Fig.11 is a schematic side sectional view of the holder 172 (Fig. 6) for holding and supporting an object to be polished, e.g., a semiconductor wafer 174. The holder 172 has an object holder 274, a backing plate 276 supporting the wafer 174, and a retaining ring 278 preventing a wafer from slipping out from the holder during polishing. In the course of polishing, the wafer is pressed towards the backing plate 276 by the applied compression force and towards the retaining ring 278 by the friction force, thus having good mechanical contact with both the backing plate and with the retaining ring. Therefore high-frequency acoustic emission sensors can be installed on and mechanically coupled to the retaining ring 278 and the backing plate 276. Also the sensors can be installed on the object holder as long as it has reliable mechanical coupling with the backing plate 276 and the retaining ring 278.

In the embodiment shown in Fig. 11, contact acoustic emission is measured by at least one of the plurality of groups of high-frequency acoustic emission sensors. A first group of high-frequency acoustic emission sensors 280 is installed on the retaining ring 278. A second group of high-frequency acoustic emission sensors 282 is mounted on the backing plate 276, and a third group of high-frequency acoustic emission sensors 284 is embedded into the object holder 274. In the preferred embodiment of the invention the acoustic emission sensors should have a frequency response bandwidth from 100 kHz up to 10 MHz and constitute piezoelectric plates (not shown) having a thickness from 0.1 mm up to 5 mm. The transducer of the apparatus of invention is also equipped with an acoustic emission processing unit 286 (Fig. 6) electrically connected to the aforementioned high-frequency acoustic emission sensors 280, 282, 284, and via the connecting device 258 to the signal receiving unit 264 of the signal processing system

262. Based on received acoustic data signals, the processing system 262 defines polishing parameters such as an average value, a peak value, and a standard deviation for the acoustic data signal over predetermined period of time, and effectively controls the polishing process.

Other parameters that can be used for effectively controlling the polishing process are temperatures of the wafer, pad, and polishing slurry. Due to the heat generated by friction in the interface between the wafer and the polishing pad, the temperatures of these parts can vary during polishing. Such variations of the temperature corresponding to variations in friction can be used as an additional indication of a transition from one layer to another. Also, intensity of a chemical reaction between the slurry components and the material on the front surface of the wafer, greatly depending on the temperature of reacting parts, can affect both the rate and uniformity of the material removal. Therefore, measuring and controlling the temperature of the slurry, wafer, and pad in close proximity of the interface between the wafer and the pad allow for more effective and reliable controlling of the polishing process.

In view of the above, the apparatus of invention further may comprise a temperature sensing device 288 (Fig. 11), e.g., a thermocouple or a resistive temperature detector, mounted on the retaining ring in proximity to the wafer front surface. The temperature sensing device 288 that generates a temperature data signal is electrically connected to a temperature processing unit 289, which is a part of the signal processing assembly 250 (Fig. 6). Polishing parameters may further include an average value, a peak value, and a standard deviation for the temperature data signal over predetermined period of time. These additional parameters may further contribute to efficiency and reliability of the polishing process control.

As it was shown above, the efficiency of polishing greatly depends on the pad surface conditions and may decrease with time as the wear of the polishing pad progresses. In polishing this problem is solved by utilizing a pad conditioning mechanism for refreshing the working surface of the pad in the course of polishing or after a period of use. Conditioning provides more stable polishing rate and better uniformity of polishing across a wafer surface. When conditioning is no more effective in deterring the degradation of the polishing pad, the pad requires replacement. Pad conditioning can be done by rubbing an abrasive (usually diamond-containing) tool or stiff brush against the pad surface for removing polishing byproducts and slurry remaining on the pad and for refresh the pad surface. A conditioning device 290 used in the apparatus of the invention as shown in Fig. 12 is mounted on a movable arm 300 and is capable of moving along the pad surface. The conditioning device has a conditioning tool 192, such as an abrasive disk or brush mounted on a conditioner shaft 294, which performs, e.g., a rotational motion. The shaft is connected to a conditioning rotary drive unit 198, which is mounted on the arm 300. The arm 300, in turn, is connected to a drive mechanism (not shown) that can be installed on the base plate 154 and is used for moving the conditioning device with the shaft 294 and the conditioning tool 292 across the pad 194 in a horizontal direction and in a vertical direction for pressing the conditioning tool 292 against the pad 94. The conditioning device 290 is mounted on the arm 300 trough a mechanical sensor 302 for sensing a compression force F3, with which the conditioning tool 292 is pressed to the polishing pad 194 in a direction perpendicular to the working surface 196 of the pad, and a mechanical sensor 304 for sensing a force F4 acting between the conditioning tool 292 and the polishing pad 194 in a direction parallel to the working surface 196 of the pad 194, i.e., a friction force. In the preferred embodiment of the invention the mechanical sensor 302 for sensing the force F3 and the mechanical sensor 304 for sensing the force F4 can be combined into a single bi-directional force sensor 306 which allows for simultaneous detecting the forces F3 and F4.

In operation, the conditioning tool 292 is pressed against the pad 194, while being rotated and moved along the pad surface 196, so that the polishing byproducts are removed, and the

working surface 196 of the pad 194 is refreshed. In response to the relative motion of the conditioning tool along the pad, the mechanical sensors 302 and 304 detect a compression force applied from the conditioning tool 292 to the pad 194 and a conditioning friction force acting in the direction parallel to the pad surface. The mechanical sensors generate conditioning output data signals relating to the compression force and the friction force. A conditioning signal processor 310, which is electrically connected to the mechanical sensors 302, 304, and 306, amplifies the aforementioned conditioning output data signals. The data processing system 262 (Fig. 5) receives the conditioning output data signals via the connecting device 258 and computes predetermined conditioning parameters, e.g., friction coefficient between the pad and the conditioning tool as a ratio of the friction force to the compression force, thus allowing for detecting surface conditions on the pad. Continuous monitoring of the pad surface conditions allows for timely reconditioning and replacing the pad and provides for uniform and repeatable polishing results.

Another embodiment of this invention is used for polishing control with a signal peak analysis A general schematic view of the apparatus of this embodiment is shown in Fig. 13. The apparatus consists of a polishing machine 420, e.g., a CMP machine intended for polishing a semiconductor wafer W and a control and monitoring system, which in Fig. 13 is shown in the form of a single box 422 drawn by broken lines. The control and monitoring system contains a control unit 423, which may be, e.g., a stand-along controller, a computer, or the like. The polishing machine 420 and the control and monitoring system 422 are interconnected via a data line L1 and feedback line L2.

The polishing machine 420 may have a configuration different from the one shown in Fig. 13, and the CMP machine shown in Fig. 13 may have different arrangement. However, in any case the CMP machine has an object-holding means, e.g., a polishing head 424 which supports an object to be polished, such as the semiconductor wafer W, and may be driven into rotation, e.g., by an electric motor 426 with a power source 428. The polishing machine has a polishing tool such as a polishing pad 430, which in the illustrated embodiment is located under the polishing head 424 and has a diameter greater than that of the object being treated. The polishing pad 430 is driven into rotation, e.g., by an electric motor 432 connected to a power source 434. Also, either a polishing head 424 or a polishing pad 430 may perform an orbital or linear reciprocating motions. In the embodiment shown in Fig. 1 these motions are performed by the polishing head 424 with the use of a carriage 436 that slides in guides 438.

A force with which the semiconductor wafer W is pressed against the polishing pad 430 is provided by means of a vertical loading mechanism shown in the form of a lead screw 440 driven into rotation by a motor 442 with a power supply 444. The lead screw 440 engages a nut 445 secured to the carriage 436.

To this point, the above description related to a conventional CMP machine. A part of the control system consists of sensors and measuring devices described in the previous embodiments. More specifically, reference numerals 446 and 448 designate AE sensors, e.g., piezoelectric transducers, embedded into different components of the polishing head 424. Fig. 14 is an example of registration of AE signals obtained during polishing of a laminated structure consisting of layers I, II, and III of materials with different physical properties. For convenience of presentation the layers I, II, and III are shown under the graph with different layers aligned with respective portions of the graph. The graph shown in Fig. 14 illustrates variation of the AE signal AE (the ordinate axis) in time (the abscissa axis). It is understood that the abscissa axis also reflects the thickness of the object being polished since the layers I, II, and III are polished out sequentially in time.

It has been found experimentally that polishing of a homogeneous material generates acoustic signals of certain regular amplitude with an extended acoustic spectrum. An RMS value of such an AE signal is represented by a layer I which has very small peaks of amplitude. The drop of the signal level on the portion C of the AE signal curve of Fig. 14 corresponds to transition from the layer I to the layer II. It can be assumed that the layer II consists of an acoustically softer material (the Hook constant is lower than in the layer I). The high positive peaks P1, P2, and P3 on the section of the graph corresponding to the layer II may be caused, e.g., by hard inclusions In1, In2, and In3 in the material of the layer II, while the low peak P4 may be caused, e.g. by a void V4 or by local delamination of the material in the layer II. The upwardly concave curve on the portion of the graph corresponding to the layer III may lead to an assumption that this layer has a non-uniform hardness or material removal.

The above example shows that defects of different physical nature can be reflected on the changes in the spectrum of signals. This is true not only for AE signals but for other electric signals, e.g. resulting from measuring electrical resistance or capacitance in contact between the polishing pad and the wafer during polishing. Defects in the semiconductor wafer can be of two types: inherent defects pre-existing in the material or on the surface of the layers (inclusions, voids, etc.) or defects that occur during polishing and caused by the polishing (scratches, cracks, delaminations, etc.). Therefore the term "changes in the object" covers both changes on the surface of the object as well as in the inner material of the object being treated.

The applicants have found that the average value of acoustic signal represents the intensity of surface interaction between the polishing pad 430 and the object being treated, e.g., the wafer W. In particular, the average acoustic signal generated by an acoustic sensor during polishing represents intensity of polishing and the rate of material removal. On the other hand, irregular peaks in an acoustic signal and the amplitude of these peaks, such as peaks P1, P2, P3, and P4 shown in Fig. 14, represent abnormalities in the polishing process. Examples of such abnormalities are defects in the material being treated, such as aforementioned delaminations, voids, micro-scratches, chipping, flaking, inclusions, micro-cracks, etc.

The applicants have found that an absolute value of the aforementioned peaks in the acoustic signal alone is not a sufficient criterion for characterization of a polishing process. Indeed, even at a relatively high average level A0 the acoustic signal may not have peaks. This case is shown in Fig. 15, where the ordinate axis corresponds to the amplitude of the acoustic signal. Such a condition would testify to the fact that polishing is carried out with high intensity, but without abnormalities. On the other hand, cases are possible when, as shown in Fig. 16 which is similar to Fig. 15, the average level of acoustic signals A1 is lower than the average level of the acoustic signal A0 of the case shown in Fig. 16, but the peaks are present and have the maximum amplitude A2 which can be lower than A0 of Fig. 15. Thus, the case of Fig. 15 may be considered acceptable, while the case of Fig. 16 may be considered unacceptable, even though the maximum level of the acoustic signal is lower than the absolute value of the average signal of the previously accepted case.

Based on these considerations and on the results of multiple experiments, the applicants have come to a conclusion that it would be more appropriate to monitor and control a polishing process by using a ratio of the maximum peak value of an acoustic signal to an average value of this signal as a criterion of the polishing process quality.

For realization of the aforementioned method the applicants have developed the control and monitoring system 22 shown schematically in Fig. 13 in the form of a single block. The aforementioned threshold of optimized values is used as an input data loaded into this system.

The control and monitoring system 422 of the apparatus of the invention is shown in more detail in Fig. 17. The system 422 contains aforementioned acoustic sensors 446, 448 (for simplification of the drawings, only two of such sensors, i.e., 446 and 448, are shown in Figs. 13 and 17, though it shall be understood that more than two acoustic sensors may be used). The sensors 446 and 448 are connected to inputs of respective wide-band amplifiers 450 and 452, intended for preliminary amplification of AE signals S1 and S2 generated by the acoustic sensors 446 and 448. Outputs of wide-band amplifiers 450 and 452 may be connected to inputs of respective signal filters 454 and 456, such as high-pass or band-pass filters. The filters may have amplifiers 458 and 460 for amplification of the filtered signals. The latter are added in an adding unit 462, based, e.g., on an operational amplifier, and the resulting signal is then sent to a RMS converter 464. Such a converter is a standard unit commercially produced, e.g., by Analog Devices, Inc. (Norwood, MA). The RMS converter converts the resulting filtered high-frequency signal S3 into a low-frequency RMS signal S4, representing an average intensity of the acoustic signal generated by the acoustic sensors 446 and 448. It is understood that only one acoustic sensor, e.g., the sensor 446 can be used in the system with the respective wide-band amplifier 450, filter 454, and amplifier 458. In this case, the adding unit 462 will not be used.

Until now, the description related to a known part of the control and monitoring system 422 which is similar to the one described in aforementioned US Patent No. 5,245,794 and which in the following description will be referred to as a signal conditioning unit 465 (Fig. 17). The distinguishing part of the control and monitoring system 422 of the invention is shown on the right side of Fig. 17 in the form of a signal analyzer 466 shown by a broken line. The signal analyzer 466 measures all aforementioned parameters of the acoustic signal, such as an average value, the maximum peak value, and the ratio of the maximum peak value to the average value. More specifically, the signal analyzer 466 contains a peak detector 68 with a timing reset unit 470. The peak detector 68 is connected to the output of the RMS converter 464 and generates a peak signal V1 (Fig. 18). The signal analyzer 66 further contains an integrating unit 472, which is connected to the output of the RMS converter 464 and generates an average-value signal V2; and a comparator 474 for generating a measured ratio signal V proportional to a ratio of the maximum peak value V1 to the average value V2 of the acoustic signal. The respective inputs of the comparator 474 are connected to the outputs of the peak detector 468 and of the integrating unit 472.

An example of a comparator 474 is shown schematically in Fig. 18, where reference numerals 476 and 478 designate logarithmic amplifiers, 480 designates a subtracting unit which subtracts one input signal from another, and 482 designates an exponential amplifier for generating a signal of a measured ratio of the aforementioned signals V1 to V2 (Fig. 18).

The apparatus of the invention operates as follows:

A semiconductor wafer W with multiple layers, the outermost of which has to be polished, is attached to the polishing head 424 so that it faces a polishing pad 430. The control and monitoring system 422 is activated, the polishing head 424 with the wafer W and the polishing pad 430 are brought into rotation from respective electric motors 426 and 432 connected to power sources 428 and 434. The polishing head 424 is then fed towards the polishing pad 430 by means of the loading mechanism formed by the lead screw 440 with the nut 445 attached to the carriage 436. The lead screw 440 is driven from the motor 442, which is fed from the power supply 444. As a result, the semiconductor wafer W comes into contact with the polishing pad 430 with a predetermined contact pressure.

The surface of the polishing pad 430 has been covered with polishing slurry SL supplied to the polishing surface of the pad from a slurry supply system 447. It is known to a person skilled in the art that the properties of the slurry and the flow rate of the slurry supply may affect the results of polishing. Therefore these factors should be controlled during polishing.

Simultaneously with rotation, the polishing head 424 may perform linear oscillating motions in the radial direction of the pad 430 by means of the carriage 436 moveable in the guides 438.

The polishing process is accompanied by high-frequency contact acoustic emission, generated in the interface between the contacting surfaces of the semiconductor wafer W and the polishing pad 430. These acoustic waves reflect changes in the object and are detected as acoustic signals by high-frequency acoustic sensors 446 and 448 built into the polishing head 424 and/or polishing pad 430. The sensors 446 and 448 generate on their outputs operating AE data signals S1 and S2, respectively. These signals may be of the type shown in Figs. 19-21 and may correspond to intensity of the polishing process. The acoustic data signals S1 and S2 (Figs. 17) are sent to respective wide-band amplifiers 450 and 452 and after amplification the signals are sent to respective filters 454 and 456, which may be of high-pass or band-pass types. These filters cut off low-frequency components, which correspond to mechanical, electrical, and environmental noise and vibrations. In other words, only high-frequency acoustic components of a desirable bandwidth pass through the filters. After amplification in amplifiers 458 and 460, the signals are summarized in the adding unit 462 and the resulting signal S3 is sent to the RMS converter 464. In the case of a single acoustic sensor, the amplified signal will be sent directly from the amplifier to the RMS converter. The RMS converter 464 generates a conditioned signal S4 (Fig. 17), which is sent as an input signal to the signal analyzer 466. It is understood that the use of the RMS converter is optional and that after amplification the resulting signal S3 can be sent directly to the signal analyzer 466.

As has been mentioned above, the AE signals may have high-amplitude random peaks of the type shown in Figs. 14 and 16, which reflect abnormalities of the polishing process. Examples of such abnormalities are such defects as aforementioned delaminations, voids, micro-scratches, chipping, flaking, inclusions, micro-cracks, etc. The function of the aforementioned signal analyzer 466, surrounded in Fig. 17 by the broken-line block, is to detect such abnormalities and to generate a ratio signal V for controlling the operation of drive motors 426, 432, and 442 of the polishing machine 420. More specifically, the motor 442 controls contact pressure between the wafer W and the polishing pad 430, while the motors 426 and 432 control rotation of the polishing head 424 and of the polishing pad 430, respectively.

In the signal analyzer 66, signal S4 is supplied to the peak detector 468 and to the integrating unit 472. The peak detector 468 generates a signal V1 that corresponds to the maximum amplitude of the peak of the conditioned AE signal S4, while the integrating unit 472 generates a signal V2 that corresponds to the average level of the same AE signal S4. The peak detector 468 and the integrating unit 472 may be connected to the timing reset unit 470 which synchronizes operation of the aforementioned devices 468 and 472. Signals V1 and V2 are sent to the inputs of the comparator 474 which, in turn, generates the aforementioned ratio signal V used by the control unit 423 for controlling operation of the polishing machine 420. The control unit 423 compares ratio signal V with an optimized reference value which can be stored, e.g., in a memory (not shown) of the control unit 423 and generates a control signal S5. The control signal S5 is sent via the feedback line L2 to the polishing machine, i.e., to motors 426, 432, 442, and the slurry supply system 447.

When the polishing process is characterized by a stable polishing rate, which corresponds to the acoustic signal without high peaks (Fig. 15), the ratio of the maximum peak amplitude to the average value of the AE signal is about 1, and therefore the ratio signal V has a low level. When, however, as shown in Fig. 16, the process is accompanied by abnormalities characterized by the presence of high peaks, the aforementioned ratio of the maximum peak amplitude to the average value of the AE signal significantly exceeds 1, and therefore the ratio signal V has a high level. The difference in the levels of the aforementioned ratio signal V can be used for controlling, via a feedback control signal S5, the operation of actuating units of the polishing machine 420, such as electric motors, for automatically adjusting parameters of the polishing process to eliminate abnormalities.

Although the invention has been shown and described with reference to specific practical examples, it is understood that these examples were given only for illustration purposes and that any other changes and modifications, including various combinations of the parts and units of the invention, are possible provided that these changes and modifications do not depart from the scope of the appended claims.

For example, the comparator of the signal analyzer can be embodied in different form known in the art. Although in the embodiments illustrated in the description of the invention both the head and the pad perform rotational motions, any of them may perform orbital or linear movements. The operation of the apparatus was illustrates with two signals S1 and S2 on the outputs of the sensors 446 and 448. It is understood, however, that only one such signal or more than two signals can be generated by one or by many acoustic sensors, respectively. The integrating unit 472 can be made in the form of a low-pass filter, an analog integrator, or as a part of control software. The peak detector 68 and the comparator 474 also can be embodied as a part of the control software. In the former embodiment with the electrical sensors, the conductive elements and contacts may have a rectangular, triangular or any other cross sectional configuration. The conductive elements, contacts, and probes can be arranged on one or more than two circular rows. An object being treated is not necessarily a layered semiconductor wafer and may comprise a workpiece of a uniform metal or ceramic material or the like. In this case changes of detectable properties on the surface being treated are caused by a decrease in microscopic unevenness or by a decrease in the thickness of the object. The rotating head may perform only a rotary motion, while the platen with the pad may perform either rotational or orbital motion in combination with a linear motion.

CLAIMS

1. An apparatus for controlled polishing of an object having a surface to be polished in a polishing process, comprising:

a frame which has a base plate and at least one vertical column;

vertical positioning means mounted on said at least one vertical column;

first drive means for moving said vertical positioning means along said at least one vertical column with respect to said base plate;

horizontal positioning means capable of performing motions in a direction parallel to said base plate;

second drive means for moving said horizontal positioning means in said direction parallel to said base plate;

a head having means for supporting an object to be treated, said head having an axis of rotation, said polishing process being characterized by predetermined polishing parameters required for optimization of said polishing process;

third drive means for rotating said head in respect to said axis of rotation;

a platen with a polishing pad attached to said platen;

polishing drive means for moving said platen with respect to said object while maintaining said pad in contact with said surface to be polished, said pad having a working surface opposed to said platen;

sensing means for sensing changes that may occur on said surface to be polished and inside said object during said polishing and for generating output data signals, said sensing means comprising a combination of at least two sensing means selected from the group consisting of contact acoustic emission sensing means for generating acoustic data signals, mechanical sensing means for generating mechanical data signals, and electrical sensing means for generating electrical data signals;

a control and monitoring system for processing said output data signals and for generating a control signal for controlling operation of said apparatus in order to maintain said predetermined polishing parameters during said polishing process.

2. The apparatus of Claim 1, wherein said control and monitoring system comprises:

a signal conditioning unit having signal acquiring means, signal amplifying means for amplifying said output data signals and conditioned signal generation means for generating conditioned signals,

a signal analyzer for combined processing of said conditioned signals and for computing polishing parameters in response to said conditioned signals,

a control unit for generating a control signal for controlling operation of said apparatus in order to optimize said polishing parameters to achieve a predefined optimization criteria by controlling at least one of drive means selected from a plurality of said first drive means, said second drive means, said third drive means, and said polishing drive means in response to variations in said polishing parameters; and

a display unit having means for monitoring signals selected from a plurality of said output data signals, said conditioned signals and said polishing parameters; and wherein said apparatus further comprises connecting means for connecting said sensing means to said control and monitoring system, said connecting means comprising a first connecting unit and a second connecting unit, said first connecting unit comprising a moveable part which moves together with said platen and a stationary part which is connected to said control and monitoring system, said second connecting unit comprising a moveable part, which moves together with said head, and a stationary part which is connected to said control and monitoring system.

3. The apparatus of Claim 1, wherein said head is capable of performing vertical, horizontal and rotary motions; said working surface being parallel to said surface to be polished, said platen having a center; said polishing drive means comprising a drive motor and a transmission unit between said drive motor and said platen, said transmission unit being selected from a rotary type transmission which imparts a rotary motion to said platen, an orbital type transmission which imparts an orbital motion to said platen, and a linear type transmission which imparts a linear motion to said platen.

4. The apparatus of Claim 3, wherein said control and monitoring system comprises:

a signal conditioning unit having signal acquiring means, signal amplifying means for amplifying said output data signals and conditioned signal generation means for generating conditioned signals,

a signal analyzer for combined processing of said conditioned signals and for computing polishing parameters in response to said conditioned signals,

a control unit for generating a control signal for controlling operation of said apparatus in order to optimize said polishing parameters to achieve a predefined optimization criteria by controlling at least one of drive means selected from a plurality of

said first drive means, said second drive means, said third drive means, and said polishing drive means in response to variations in said polishing parameters; and

a display unit having means for monitoring signals selected from a plurality of said output data signals, said conditioned signals and said polishing parameters; and wherein said apparatus further comprises connecting means for connecting said sensing means to said control and monitoring system, said connecting means comprising a first connecting unit and a second connecting unit, said first connecting unit comprising a moveable part which moves together with said platen and a stationary part which is connected to said control and monitoring system, said second connecting unit comprising a moveable part, which moves together with said head, and a stationary part which is connected to said control and monitoring system.

5. The apparatus of Claim 1, wherein said mechanical sensing means comprises:

a first force sensor for detecting a first force acting in a first direction perpendicular to said surface to be polished and generating polish compression data signals, and

a friction sensing means for generating polish friction data signals and selected from a second force sensor for detecting a second force acting in a second direction parallel to said surface to be polished, and a torque sensor for detecting a torque acting in respect to an axis parallel to said first direction.

6. The apparatus of Claim 4, wherein said mechanical sensing means comprises:

a first force sensor for detecting a first force acting in a first direction perpendicular to said surface to be polished and generating polish compression data signals, and

a friction sensing means for generating polish friction data signals and selected from a second force sensor for detecting a second force acting in a second direction parallel to said surface to be polished, and a torque sensor for detecting a torque acting in respect to an axis parallel to said first direction.

7. The apparatus of Claim 5, wherein said polishing parameters comprise a plurality of parameters selected from at least two of the groups consisting of acoustic parameters, mechanical parameters, and electrical parameters, said mechanical parameters being selected from the group consisting of: said first force; said second force; said torque; a

polishing friction coefficient defined as a ratio of said second force to said first force; and a friction coefficient defined as a ratio of said torque to said first force.

8. The apparatus of Claim 6, wherein said polishing parameters comprise a plurality of parameters selected from at least two of the groups consisting of acoustic parameters, mechanical parameters, and electrical parameters, said mechanical parameters being selected from the group consisting of: said first force; said second force; said torque; a polishing friction coefficient defined as a ratio of said second force to said first force; and a friction coefficient defined as a ratio of said torque to said first force.

9. The apparatus of Claim 7, wherein each of said acoustic parameters, mechanical parameters, and electrical parameters has an average value, a peak value, and a standard deviation computed over predetermined period of time.

10. The apparatus of Claim 8, wherein each of said acoustic parameters, mechanical parameters, and electrical parameters has an average value, a peak value, and a standard deviation computed over predetermined period of time.

11. The apparatus of Claim 5, wherein said mechanical sensing means are combined into a single bi-directional sensor detecting both said first force acting in a first direction and at least one of said second force acting in a second direction and a torque acting in respect to an axis parallel to said first direction.

12. The apparatus of Claim 6, wherein said mechanical sensing means are combined into a single bi-directional sensor detecting both said first force acting in a first direction and at least one of said second force acting in a second direction and a torque acting in respect to an axis parallel to said first direction.

13. The apparatus of Claim 2, wherein said mechanical sensing means comprises:

first mechanical sensing means associated with said platen and electrically connected to said moveable part of said first connecting unit; and

second mechanical sensing means associated with said head and electrically connected to said moveable part of said second connecting unit.

14. The apparatus of Claim 13, wherein said platen has a drive shaft, and said first mechanical sensing means comprise at least one sensor installed on said drive shaft of said rotating platen; said head having a drive shaft, and said second mechanical sensing means comprising at least one sensor installed on said drive shaft of said head.

15. The apparatus of Claim 4, wherein said mechanical sensing means comprises:

first mechanical sensing means associated with said platen and electrically connected to said moveable part of said first connecting unit; and

second mechanical sensing means associated with said head and electrically connected to said moveable part of said second connecting unit.

16. The apparatus of Claim 15, wherein said platen has a drive shaft, and said first mechanical sensing means comprise at least one sensor installed on said drive shaft of said rotating platen; said head having a drive shaft, and said second mechanical sensing means comprising at least one sensor installed on said drive shaft of said head.

17. The apparatus of Claim 1, wherein said head comprises a retaining ring, a backing plate, and an object holder, and said contact acoustic emission sensing means comprises a plurality of groups of high-frequency acoustic emission sensors selected from a first group of high-frequency acoustic emission sensors installed on said retaining ring, a second group of high-frequency acoustic emission sensors mounted on said backing plate, and a third group of high-frequency acoustic emission sensors embedded into said object holder.

18. The apparatus of Claim 4, wherein said head comprises a retaining ring, a backing plate, and an object holder, and said contact acoustic emission sensing means comprises a plurality of groups of high-frequency acoustic emission sensors selected from a first group of high-frequency acoustic emission sensors installed on said retaining ring, a second group of high-frequency acoustic emission sensors mounted on said backing plate, and a third group of high-frequency acoustic emission sensors embedded into said object holder.

19. The apparatus of Claim 17, wherein said groups of high-frequency acoustic emission sensors comprise acoustic emission sensors with a frequency response bandwidth from 100 kHz to 10 MHz, having piezoelectric plates with a thickness from 0.1 mm to 5 mm,

said control and monitoring system contains an acoustic measurement unit comprising at least a wide-band amplifier and a band-pass filter.

20. The apparatus of Claim 18, wherein said groups of high-frequency acoustic emission sensors comprise acoustic emission sensors with a frequency response bandwidth from 100 kHz to 10 MHz, having piezoelectric plates with a thickness from 0.1 mm to 5 mm, said control and monitoring system contains an acoustic measurement unit comprising at least a wide-band amplifier and a band-pass filter.

21. The apparatus of Claim 1, further comprising a slurry supplying means for supplying a polishing slurry onto said working surface of said pad, and said control signal controlling at least one of means selected from the group consisting of said slurry supplying means, said first drive means, said second drive means, said third drive means, and said polishing drive means.

22. The apparatus of Claim 4, further comprising a slurry supplying means for supplying a polishing slurry onto said working surface of said pad, and said control signal controlling at least one of means selected from the group consisting of said slurry supplying means, said first drive means, said second drive means, said third drive means, and said polishing drive means.

23. The apparatus of Claim 1, further comprising a conditioning means for conditioning said working surface of said pad, said conditioning means being brought in contact with said working surface to remove polishing byproducts from said working surface and to refresh said working surface, said conditioning means is selected from brushing means and abrasive means.

24. The apparatus of Claim 4, further comprising a conditioning means for conditioning said working surface of said pad, said conditioning means being brought in contact with said working surface to remove polishing byproducts from said working surface and to refresh said working surface, said conditioning means is selected from brushing means and abrasive means.

25. The apparatus of Claim 23, further comprising a conditioning sensing means for combined sensing of a third force acting between said conditioning means and said

polishing pad in a third direction perpendicular to said working surface of said pad, and a fourth force acting between said conditioning means and said polishing pad in a fourth direction parallel to said working surface of said pad, said conditioning sensing means comprising a third force sensor detecting said third force and a fourth force sensor detecting said fourth force, said conditioning sensing means being electrically connected to said signal control and monitoring system; said control and monitoring system further comprising a conditioning unit for amplifying and conditioning data signals from said third force sensor and fourth force sensor; said polishing parameters further comprising parameters selected from the group consisting of: said third force, said fourth force, and a conditioning friction coefficient defined as a ratio of said fourth force to said third force.

26. The apparatus of Claim 25, wherein said polishing parameters further comprising an average value, a peak value, and a standard deviation computed over predetermined period of time for said third force; an average value, a peak value, and a standard deviation computed over predetermined period of time for said fourth force; and an average value, a peak value, and a standard deviation computed over predetermined period of time for said conditioning friction coefficient.

27. The apparatus of Claim 24, further comprising a conditioning sensing means for combined sensing of a third force acting between said conditioning means and said polishing pad in a third direction perpendicular to said working surface of said pad, and a fourth force acting between said conditioning means and said polishing pad in a fourth direction parallel to said working surface of said pad, said conditioning sensing means comprising a third force sensor detecting said third force and a fourth force sensor detecting said fourth force, said conditioning sensing means being electrically connected to said signal control and monitoring system; said control and monitoring system further comprising a conditioning unit for amplifying and conditioning data signals from said third force sensor and fourth force sensor; said polishing parameters further comprising parameters selected from the group consisting of: said third force, said fourth force, and a conditioning friction coefficient defined as a ratio of said fourth force to said third force.

28. The apparatus of Claim 27, wherein said polishing parameters further comprising an average value, a peak value, and a standard deviation computed over predetermined period of time for said third force; an average value, a peak value, and a standard deviation computed over predetermined period of time for said fourth force; and an

average value, a peak value, and a standard deviation computed over predetermined period of time for said conditioning friction coefficient.

29. The apparatus of Claim 25, wherein said conditioning sensing means comprises a combined single bi-directional force sensor detecting both said third force acting in said third direction and said fourth force acting in said fourth direction.

30. The apparatus of Claim 27, wherein said conditioning sensing means comprises a combined single bi-directional force sensor detecting both said third force acting in said third direction and said fourth force acting in said fourth direction.

31. The apparatus of Claim 1, wherein said head comprises a retaining ring, said sensing means for sensing changes that occur between said surface to be polished and said working surface of said pad during said polishing process further comprising a temperature sensing means mounted on said retaining ring, generating a temperature data signal, and electrically connected to said control and monitoring system; said polishing parameters further comprising an average value, a peak value and a standard deviation computed over predetermined period of time for said temperature data signal.

32. The apparatus of Claim 4, wherein said head comprises a retaining ring, said sensing means for sensing changes that occur between said surface to be polished and said working surface of said pad during said polishing process further comprising a temperature sensing means mounted on said retaining ring, generating a temperature data signal, and electrically connected to said control and monitoring system; said polishing parameters further comprising an average value, a peak value and a standard deviation computed over predetermined period of time for said temperature data signal.

33. The apparatus of Claim 31, wherein said sensing means for sensing changes that may occur on said surface to be polished and inside said object during said polishing further comprises a temperature sensing means for detecting temperature inside the slurry and generating a slurry temperature data signal, said temperature sensing means being electrically connected to said control and monitoring system; said polishing parameters further comprising an average value, a peak value and a standard deviation computed over predetermined period of time for said slurry temperature data signal.

34. The apparatus of Claim 32, wherein said sensing means for sensing changes that may occur on said surface to be polished and inside said object during said polishing further comprises a temperature sensing means for detecting temperature inside the slurry and generating a slurry temperature data signal, said temperature sensing means being electrically connected to said control and monitoring system; said polishing parameters further comprising an average value, a peak value and a standard deviation computed over predetermined period of time for said slurry temperature data signal

35. The apparatus of Claim 1, further comprising a first position detecting means for detecting position of said head in respect to said platen, said first position detecting means generating vertical position data signal, being mechanically coupled with said first drive means and electrically connected to said control and monitoring system.

36. The apparatus of Claim 1, further comprising a second position detecting means for detecting position of said axis of said head in respect to a center of said platen, said second position detecting means generating lateral position data signal, being mechanically coupled with said second drive means and electrically connected to said control and monitoring system.

37. The apparatus of Claim 35, further comprising a second position detecting means for detecting position of said axis of said head in respect to a center of said platen, said second position detecting means generating lateral position data signal, being mechanically coupled with said second drive means and electrically connected to said control and monitoring system.

38. The apparatus of Claim 1, wherein said platen has a center, said electrical sensing means comprising a plurality of electrical probes selected from at least one group of electrical resistance measurement probes and electrical capacitance measurement probes built into said platen and said pad and arranged circumferentially in at least one circular row concentrically with respect to said center of said platen.

39. The apparatus of Claim 4, wherein said electrical sensing means comprising a plurality of electrical probes selected from at least one group of electrical resistance measurement probes and electrical capacitance measurement probes built into said

platen and said pad and arranged circumferentially in at least one circular row concentrically with respect to said center of said platen

40. The apparatus of Claim 39, further comprising a source of electric current, wherein each of said electrical resistance measurement probes comprises at least a first pair of electrically-conductive elements, exposed to said working surface of said pad and electrically connectable to said source of electric current, and at least a second pair of electrically-conductive elements exposed to said working surface of said pad and being electrically connected to said moveable part of said first connecting unit, which, in turn, is electrically connected to said control and monitoring system; said control and monitoring system further comprising an electrical resistance measurement unit, said electrical resistance measurement unit comprising at least a first current source, a voltage drop signal conditioner, and a first commutation circuitry.

41. The apparatus of Claim 39, further comprising a source of an alternating electric current, wherein each of said electrical capacitance measurement probes comprises at least a first electrically-conductive element, exposed to said working surface of said pad, and electrically connectable to said source of alternating electric current, and a second electrically-conductive element, exposed to said working surface of said pad, and being electrically connected to said moveable part of said first connecting unit, which, in turn, is electrically connected to said control and monitoring system; said control and monitoring system further comprising an electrical capacitance measurement unit, said capacitance measurement unit comprising at least a second alternating current source, a current-to-voltage converter, an output signal conditioner, and a second commutation circuitry.

42. The apparatus of Claim 41, further comprising a source of electric current, wherein each of said electrical resistance measurement probes comprises at least a first pair of electrically-conductive elements, exposed to said working surface of said pad and electrically connectable to said source of electric current and at least a second pair of electrically-conductive elements exposed to said working surface of said pad, and electrically connected to said control and monitoring system; said control and monitoring system further comprising an electrical resistance measurement unit.

43. The apparatus of Claim 38, wherein each said electrically-conductive element of each said group comprises a resilient conductive pin embedded into said pad and a contact element in said platen.

44. The apparatus of Claim 39, wherein each said electrically-conductive element of each said group comprises a resilient conductive pin embedded into said pad and a contact element in said platen.

45. The apparatus of Claim 2, wherein said signal analyzer comprises: means for determining average values of said conditioned signals; means for determining peak values of said conditioned signals; means for generating a measured ratio signal proportional to a ratio of said peak signals to said average signals.

46. The apparatus of Claim 45, further comprising a feedback line that connects said control unit, which generates a control signal, with said first drive means, said second drive means, said third drive means, and said polishing drive means.

47. The apparatus of Claim 22, further comprising a feedback line that connects said control unit, which generates a control signal, with said first drive means, said second drive means, said third drive means, said polishing drive means, and said polishing slurry supply means.

48. The apparatus of Claim 17, wherein said signal analyzer comprises: means for determining average values of said conditioned signals; means for determining peak values of said conditioned signals; means for generating a measured ratio signal proportional to a ratio of said peak signals to said average signals.

49. The apparatus of Claim 18, wherein said signal analyzer comprises: means for determining average values of said conditioned signals; means for determining peak values of said conditioned signals; means for generating a measured ratio signal proportional to a ratio of said peak signals to said average signals.

50. The apparatus of Claim 48, wherein said signal analyzer comprises an RMS converter.

51. The apparatus of Claim 49, wherein said signal analyzer comprises an RMS converter.

52. The apparatus of Claim 50, wherein said signal analyzer comprises: an integrating unit for generating an average level of said conditioned signal, said integrating unit having an input and output, said input of said integrating unit being connected to said signal conditioning unit; a peak detector having an input and output, said input of said peak detector being connected to said signal conditioning unit; and a comparator having an output, a first input connected to said output of said integrating unit, and a second input connected to said output of said peak detector, said output of said comparator being connected to said control unit.

53. The apparatus of Claim 51, wherein said signal analyzer comprises: an integrating unit for generating an average level of said conditioned signal, said integrating unit having an input and output, said input of said integrating unit being connected to said signal conditioning unit; a peak detector having an input and output, said input of said peak detector being connected to said signal conditioning unit; and a comparator having an output, a first input connected to said output of said integrating unit, and a second input connected to said output of said peak detector, said output of said comparator being connected to said control unit.

54. A method for controlling a polishing process of an object having a surface to be polished, said method comprising the steps of:

providing a polishing apparatus comprising a moveable platen having a drive shaft and a replaceable pad, a head having a drive shaft and capable of performing rotary motions, said replaceable pad and said head having a relative linear motion, said head having means for supporting said object, said object having a surface to be polished; sensing means for sensing changes that may occur on said surface to be polished and inside said object during said polishing process, said sensing means generating output data signals and comprising a plurality of at least two sensing means selected from the group consisting of mechanical sensing means for generating mechanical data signals, contact acoustic emission sensing means for generating acoustic data signals, and electrical sensing means for generating electrical data signals; a control and monitoring system, and connecting means; said polishing process being characterized by predetermined polishing parameters required for optimization of said process of polishing;

polishing said object in said polishing process by means of said polishing

apparatus;

sensing changes that may occur on said surface to be polished and inside of said object during said polishing process simultaneously by means of said at least two sensing means;

processing said data signals obtained from said at least two sensing means by said control and monitoring system; and

controlling said polishing process in response to said steps of sensing and processing for maintaining said predetermined polishing parameters during said polishing process.

55. The method of Claim 54, wherein said processing of said data signals comprises steps of:

conditioning said data signals, comprising acquiring said data signals, amplifying said data signals and generating conditioned signals,

analyzing said conditioned signals and computing said polishing parameters in response to said conditioned signals;

and wherein controlling said polishing process comprises steps of:

generating a control signal and

sending said control signal to said polishing apparatus.

56. The method of Claim 55, wherein said polishing apparatus is a chemical mechanical polishing machine, which further comprises means for moving said replaceable pad, means for moving said head, loading means for creating contact pressure between said object and said replaceable pad, and polishing slurry supply means; said step of sending said control signal to at least one of said means for moving said replaceable pad, said means for moving said head, said loading means for creating contact pressure between said object and said replaceable pad, and said polishing slurry supply means.

57. The method of Claim 54, wherein said mechanical sensing means comprise a first force sensor and a friction sensing means selected from a second force sensor and a torque sensor, said sensing of said changes comprises detecting a first force acting in a first direction perpendicular to said surface to be polished and generating polish compression data signals, and detecting a polishing friction data signals selected from a second force acting in a second direction parallel to said surface to be polished and a torque acting in respect to an axis parallel to said first direction.

58. The method of Claim 57, wherein said predetermined polishing parameters comprise a combination of parameters selected from at least two of the groups consisting of acoustic parameters, mechanical parameters, and electrical parameters, said mechanical parameters being selected from the group consisting of: said first force; said second force; said torque; a polishing friction coefficient defined as a ratio of said second force to said first force; and a friction coefficient defined as a ratio of said torque to said first force.

59. The method of Claim 58, wherein each of said acoustic parameters, mechanical parameters, and electrical parameters has an average value, a peak value, and a standard deviation computed over predetermined period of time.

60. The method of Claim 54, wherein said replaceable pad is made of a non-conductive material, said object having a multiplayer structure with a conductive external layer which is in contact with said replaceable pad and said electrical sensing means, and a next non-conductive layer, said controlling comprising detection of an end point of said polishing process at which said conductive external layer is completely removed and said electrical sensing means come into contact with said next non-conductive layer.

61. The method of Claim 54, wherein said replaceable pad is made of a non-conductive material, said object having a multiplayer structure with a nonconductive external layer which is in contact with said replaceable pad and said electrical sensing means, and a next conductive layer, said controlling comprising detection of an end point of said polishing process at which said nonconductive external layer is completely removed and said electrical sensing means come into contact with said next conductive layer.

62. The method of Claim 60, wherein said electrical sensing means further comprise at least one sensor selected from a plurality of electrical resistance measurement probes and electrical capacitance measurement probes.

63. The method of Claim 61, wherein said electrical sensing means further comprise at least one sensor selected from a plurality of electrical resistance measurement probes and electrical capacitance measurement probes.

64. The method of Claim 61, wherein said analyzing of said conditioned signals and computing said polishing parameters comprise:

detecting and analyzing peaks of said conditioned signals;

determining a peak level and an average level of said conditioned signals; and

determining a ratio of said peak level to said average level and generating a ratio signal;

and wherein said generating a said control signal is based on said ratio signal and said average level.

65. The method of Claim 64, wherein said sensing means comprise at least one high-frequency acoustic emission sensor with a frequency response bandwidth from 100 kHz to 10 MHz, said conditioning said acoustic data signals comprises steps of wide-band amplification and band-pass filtering.

66. The method of Claim 65, wherein said step of processing said acoustic data signals in said control and monitoring system comprises passing said acoustic data signals sequentially through a wide-band amplifier and an RMS converter, said conditioned signals having peaks.

67. The method of Claim 65, further comprising a step of passing said acoustic data signal through a filter selected from a group consisting of a high-pass filter and a band-pass filter installed between said wide-band amplifier and said RMS converter.

68. The method of Claim 64, wherein said step of determining said ratio comprises: providing said control and monitoring system with a signal analyzer comprising an integrating unit, a peak detector, and a comparator; sending said conditioned signals to said peak detector for generating a peak level signal that corresponds to the maximum amplitude of said peaks of said conditioned signals; sending said conditioned signals to said integrating unit for generating an average level signal that corresponds to the average level of said conditioned signals; and sending said peak level signal and said average level signal to said comparator for obtaining said ratio signal.

69. The method of Claim 68, further comprising the steps of: detecting abnormalities in said operation of polishing by detecting and analyzing said peaks of said acoustic data

signals; and sending said control signal to said polishing apparatus for eliminating said abnormalities.

70. The method of Claim 69, wherein said abnormalities are selected from a group consisting of delaminations, voids, micro-scratches, chipping, flaking, inclusions, and micro-cracks in said object.

71. The method of Claim 54, further providing the steps of:

computing current parameters of said process of polishing based on said data signals generated by said at least two sensing means:

comparing said current parameters with said predetermined parameters of said process of polishing; and

performing said step of controlling in response to said steps of measuring and combined processing, computing, and comparing.

72. The method of Claim 55, wherein said sensing means for sensing said changes further comprise temperature sensing means generating temperature data signals; said method comprising the steps of:

arranging said temperature sensing means in a device selected from the group consisting of said head, said means for supporting an object to be treated, said replaceable pad and said slurry supplying means;

measuring variations in polishing temperature by said temperature sensing means;

processing said temperature data signals by means of said control and monitoring system and

controlling said process of polishing in response to said steps of measuring and processing.

73. The method of Claim 72, wherein said polishing parameters further comprising an average value, a peak value, and a standard deviation computed over predetermined period of time for said temperature data signals.

74. The method of Claim 54, wherein said polishing apparatus further comprises conditioning means for conditioning said replaceable pad and a conditioning sensing means generating conditioning data signals for sensing a third force acting between said

conditioning means and said polishing pad in a direction perpendicular to said replaceable pad, and a fourth force acting between said conditioning means and said replaceable pad in a fourth direction parallel to said replaceable pad, said method comprising the steps of:

bringing said conditioning means in contact with said replaceable pad to remove polishing byproducts and to refresh said replaceable pad;

measuring said third force and said fourth force with said conditioning sensing means;

processing said conditioning data signals by means of said control and monitoring system; and

controlling said conditioning of said replaceable pad in response to said steps of measuring and processing said conditioning data signals.

75. The method of Claim 74, wherein said polishing parameters further comprising parameters selected from the group consisting of: said third force, said fourth force, and a conditioning friction coefficient defined as a ratio of said fourth force to said third force.

76. The method of Claim 75, wherein said polishing parameters further comprising an average value, a peak value, and a standard deviation computed over predetermined period of time for said third force; an average value, a peak value, and a standard deviation computed over predetermined period of time for said fourth force; and an average value, a peak value, and a standard deviation computed over predetermined period of time for said conditioning friction coefficient.

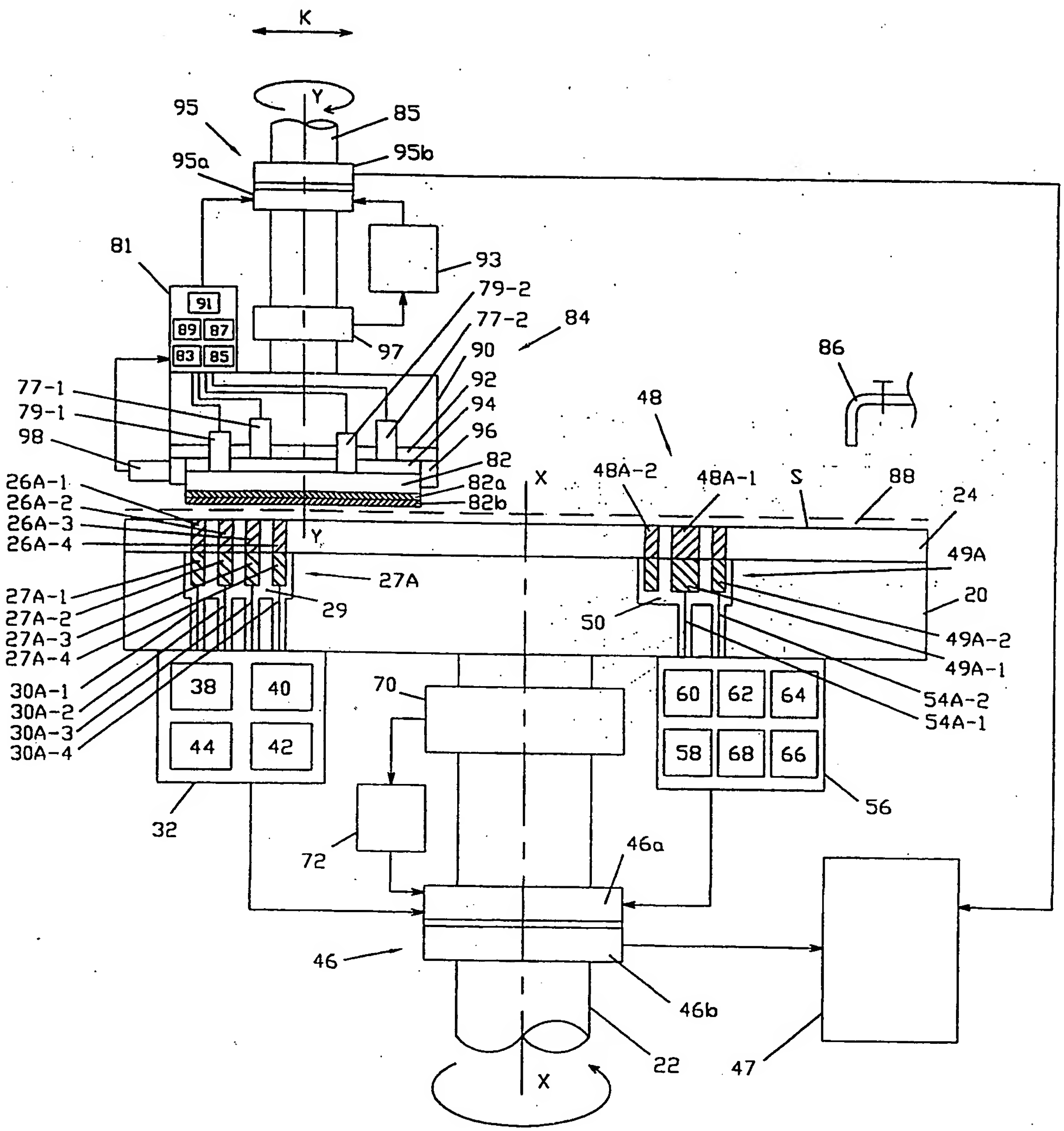
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Fig. 1

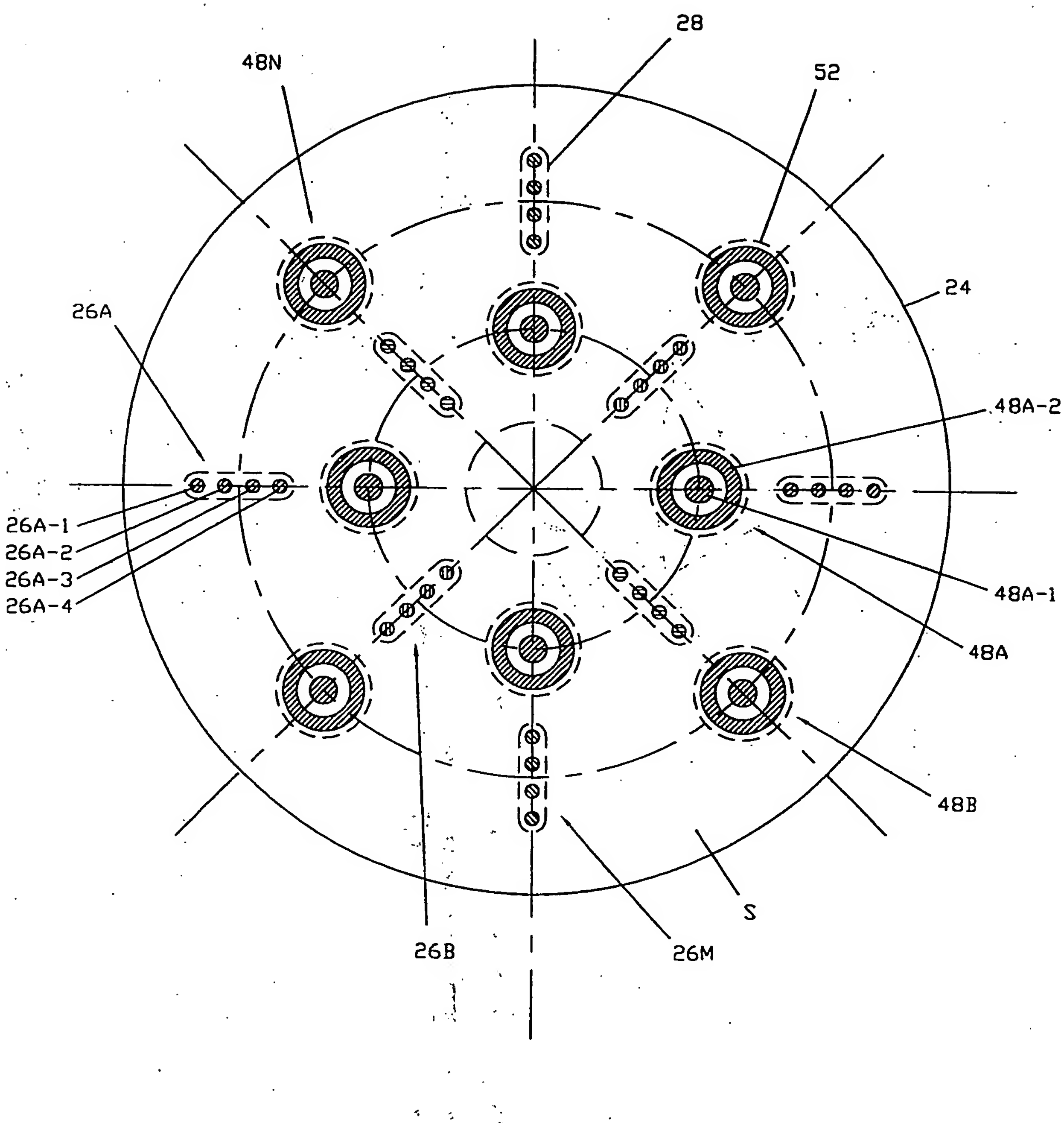


Fig. 2

Fig. 3a

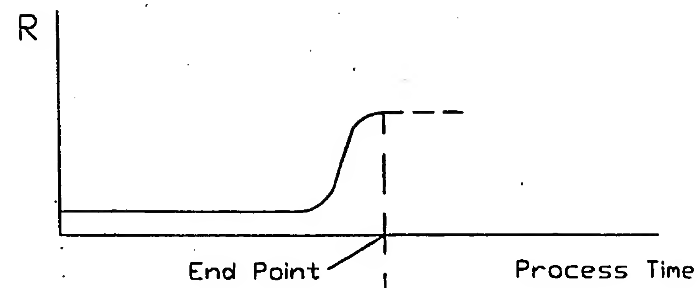


Fig. 3b

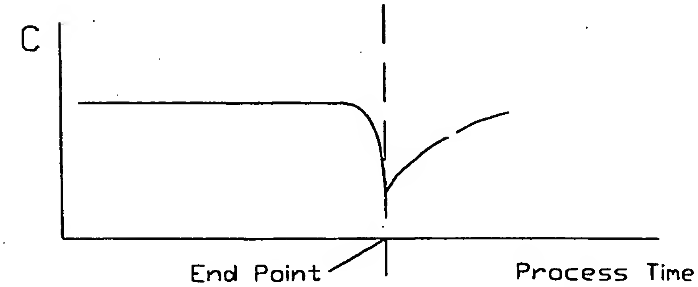


Fig. 3c

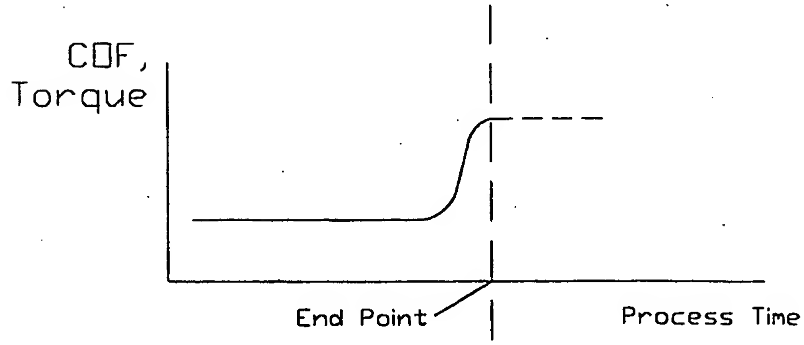


Fig. 3d

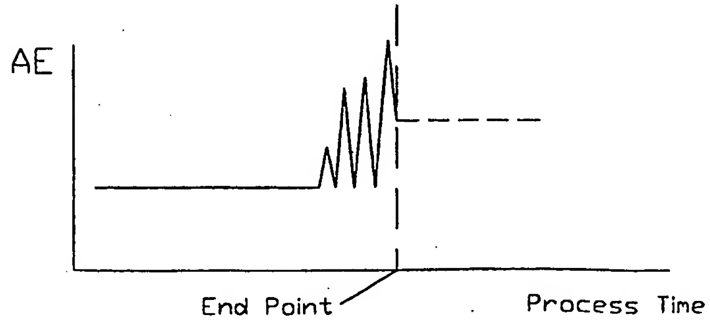


Fig. 4a

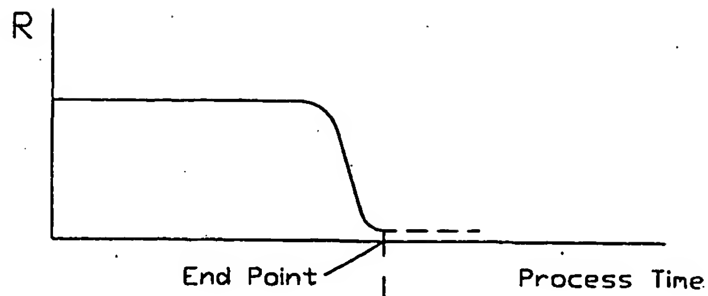


Fig. 4b

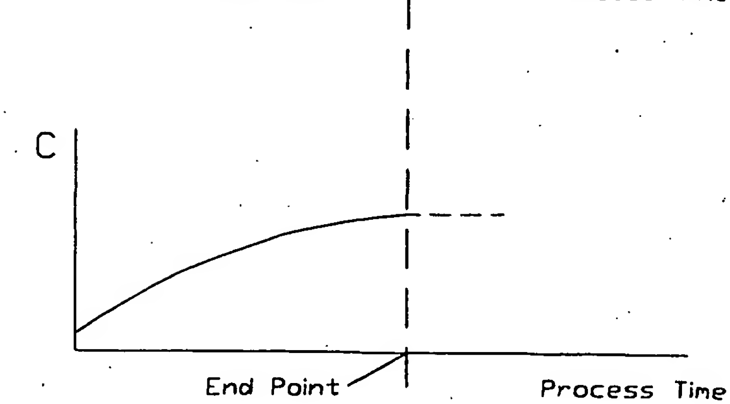


Fig. 4c

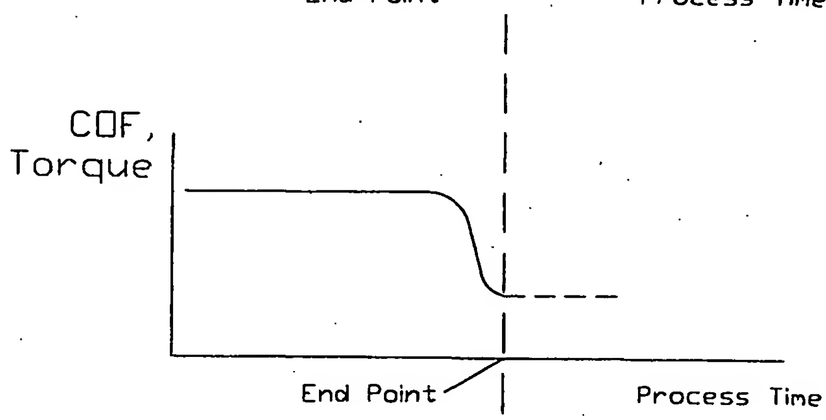
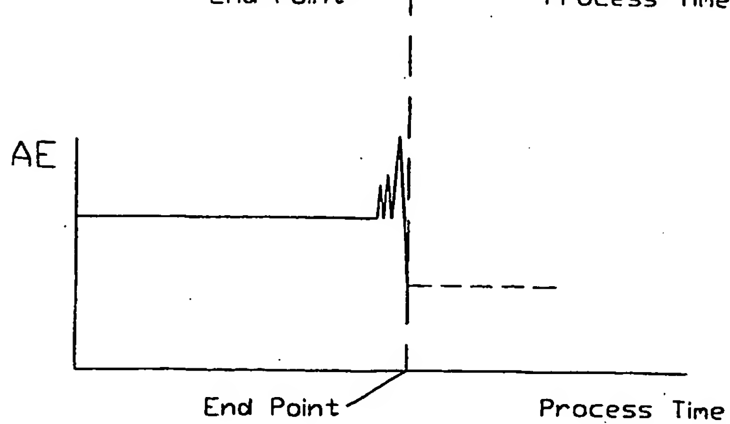


Fig. 4d



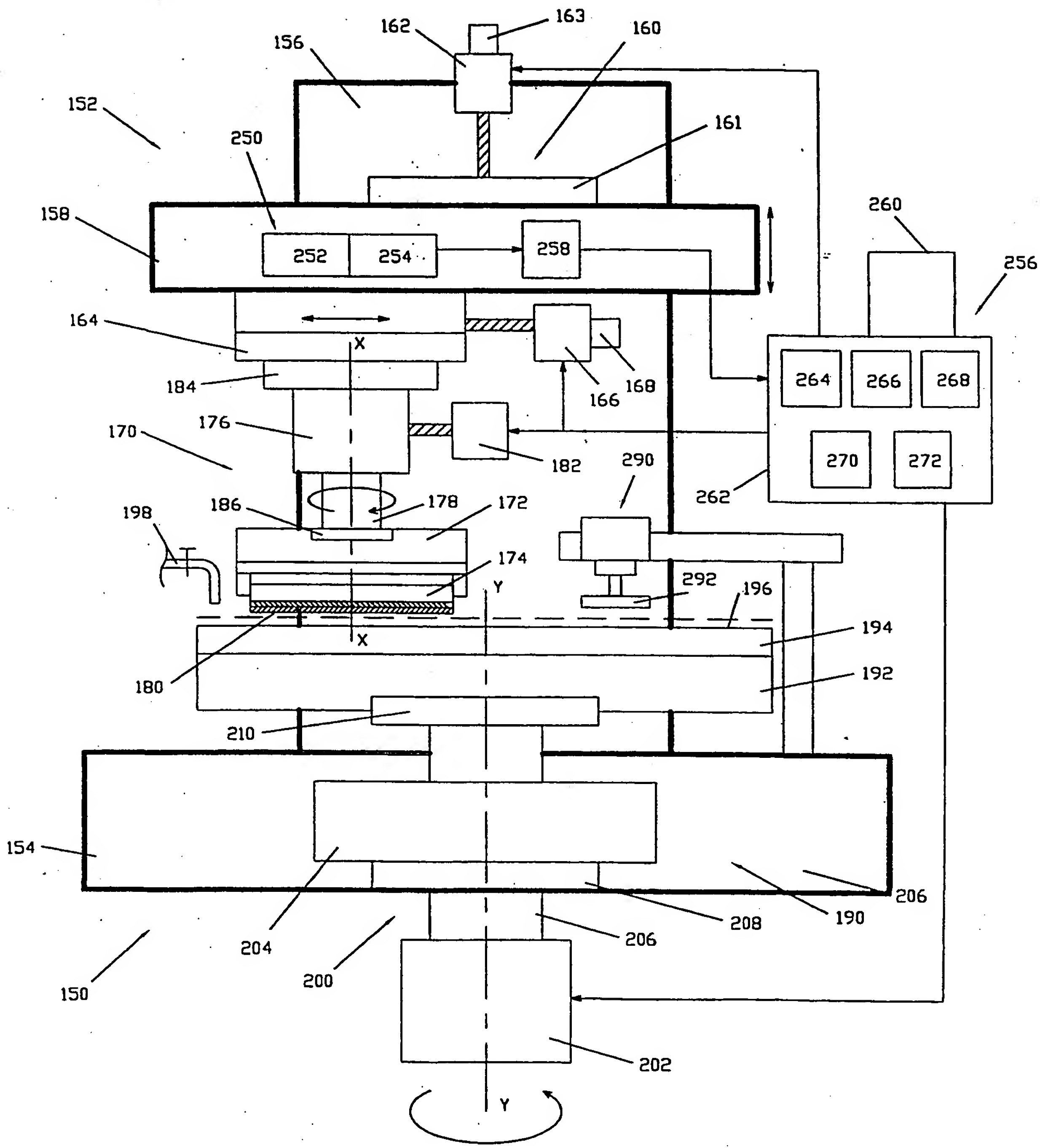

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Fig. 5

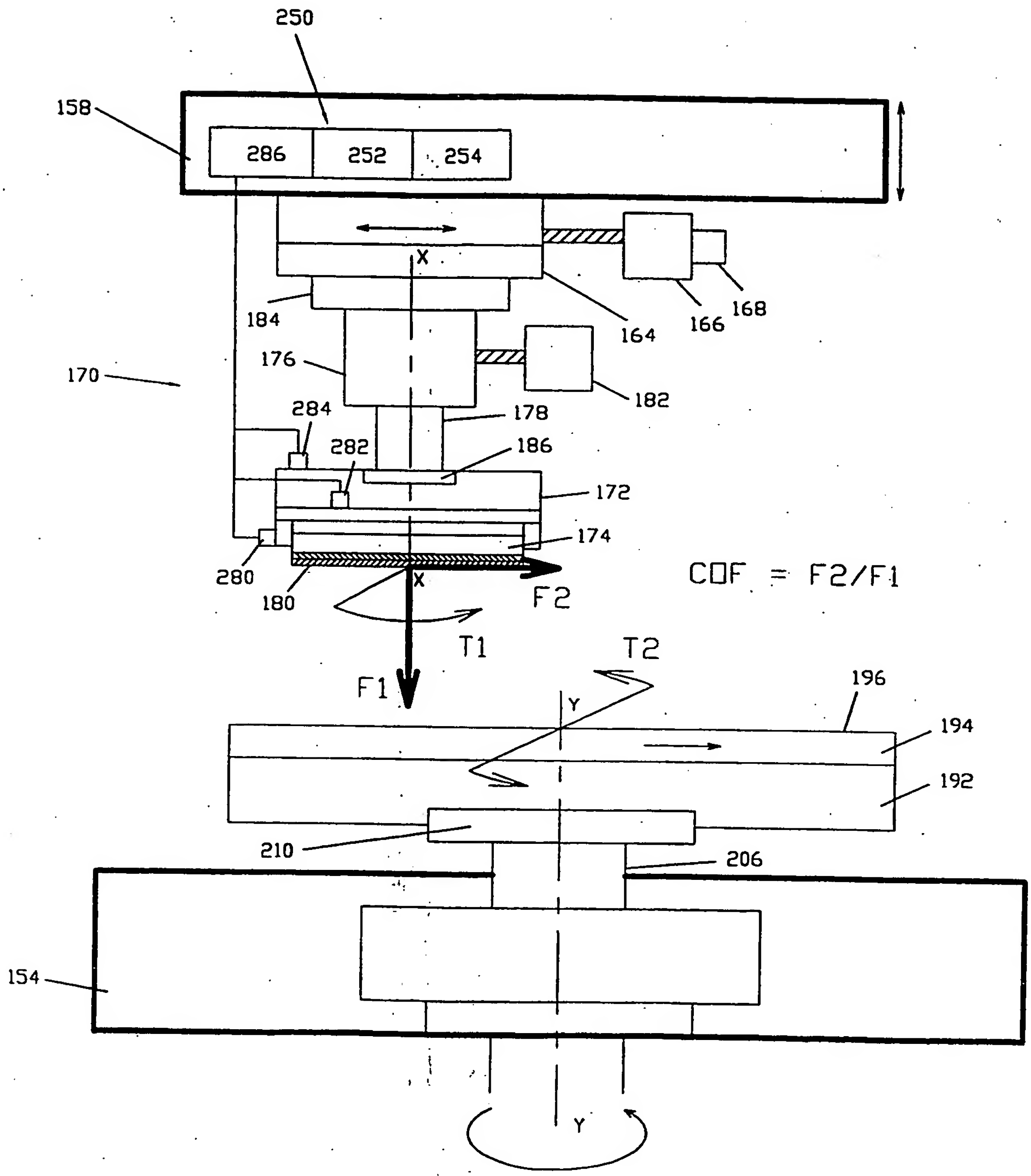
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Fig. 6

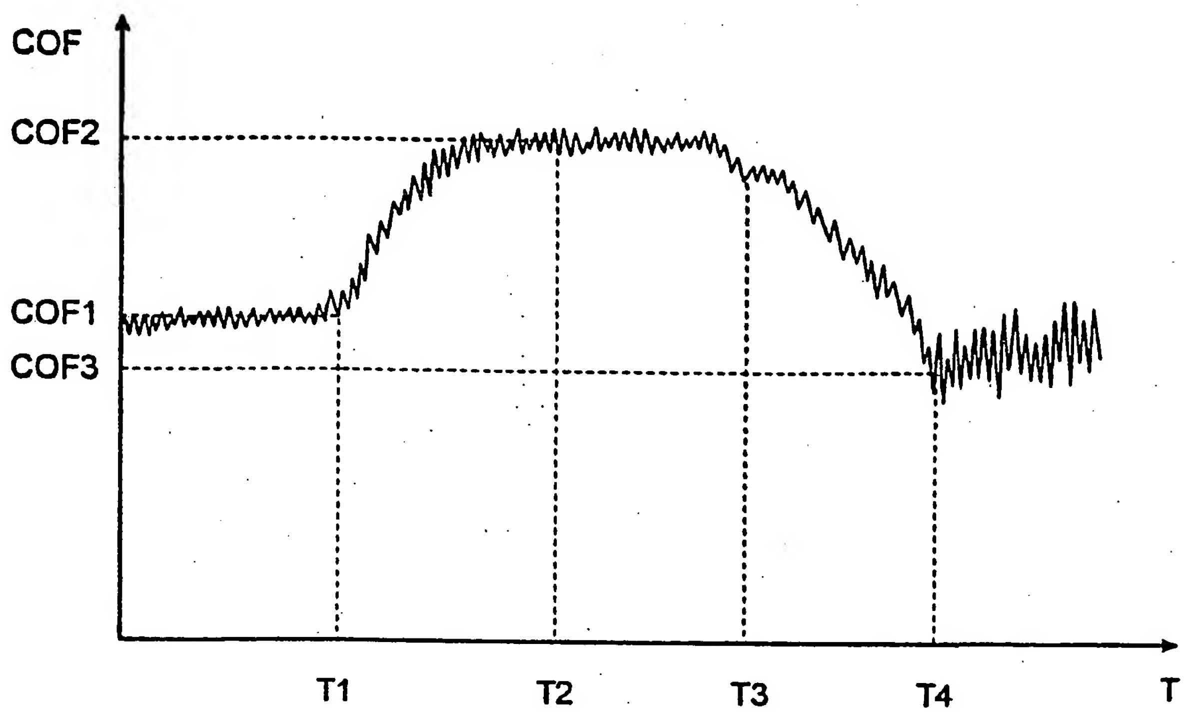

FIG. 7

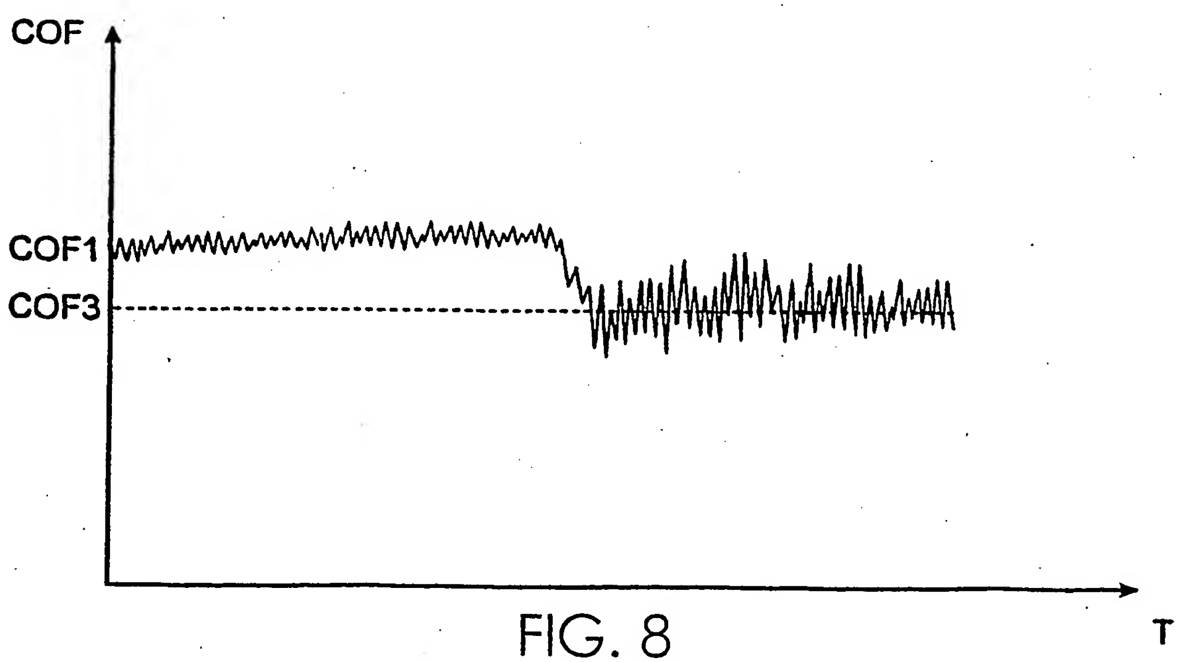

FIG. 8

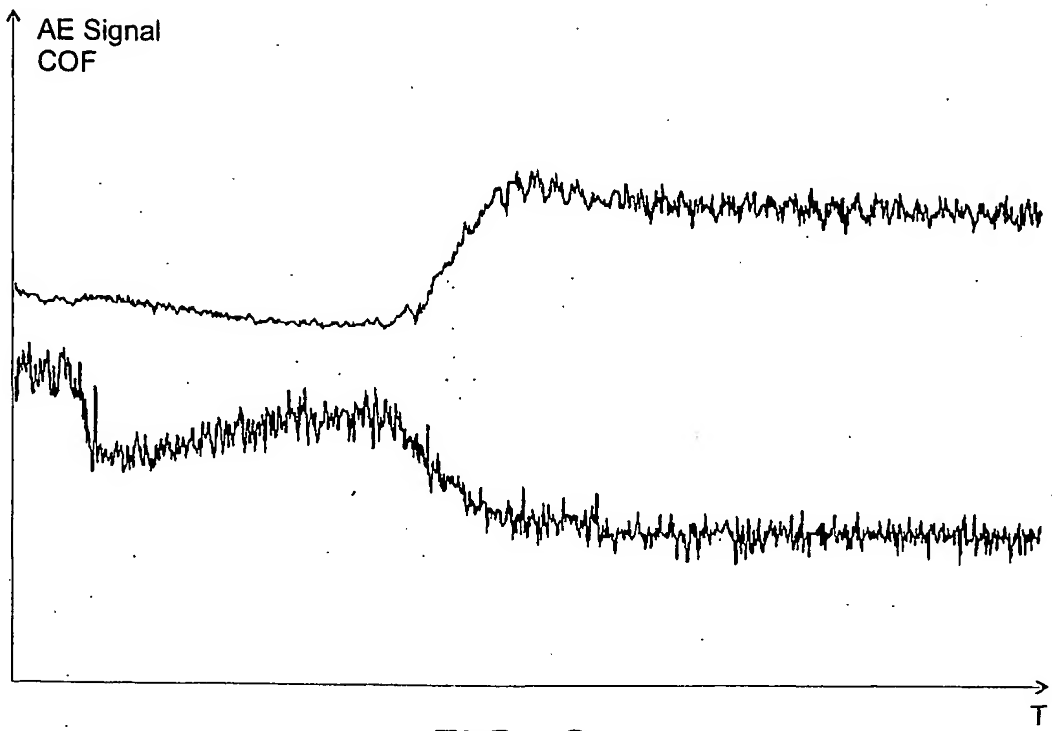

FIG. 9

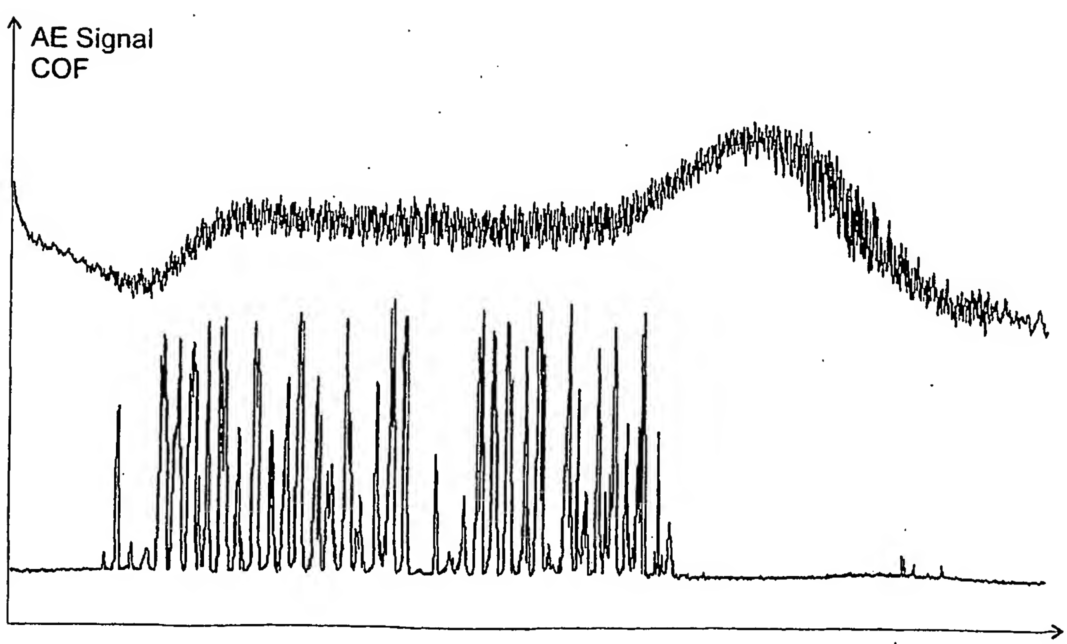

FIG. 10

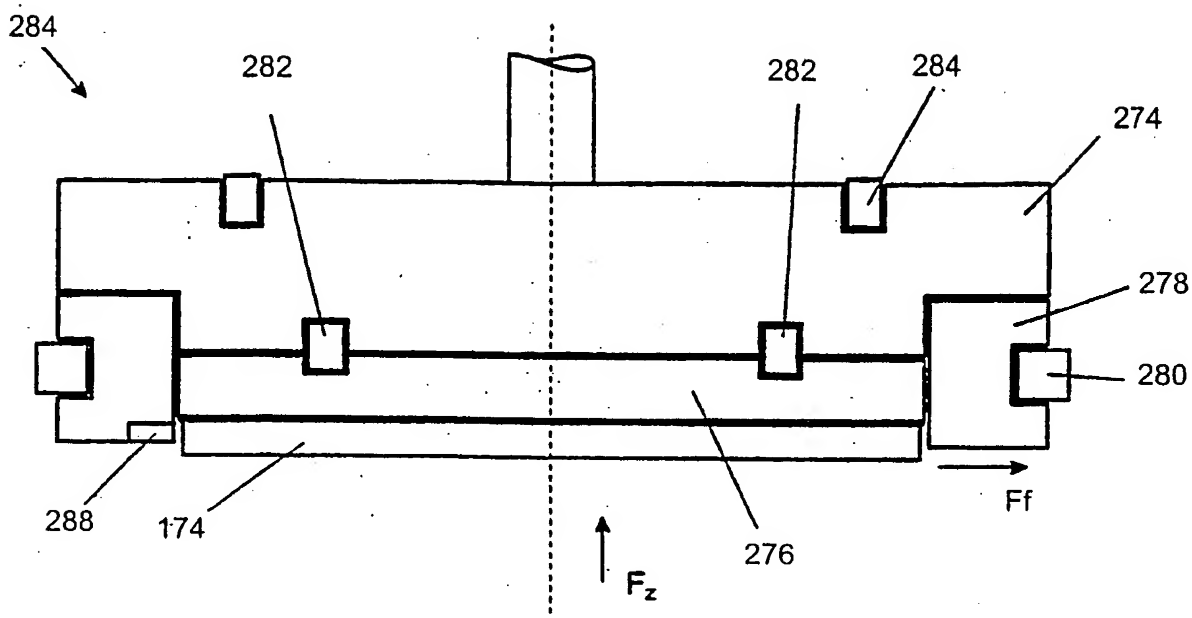
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FIG. 11

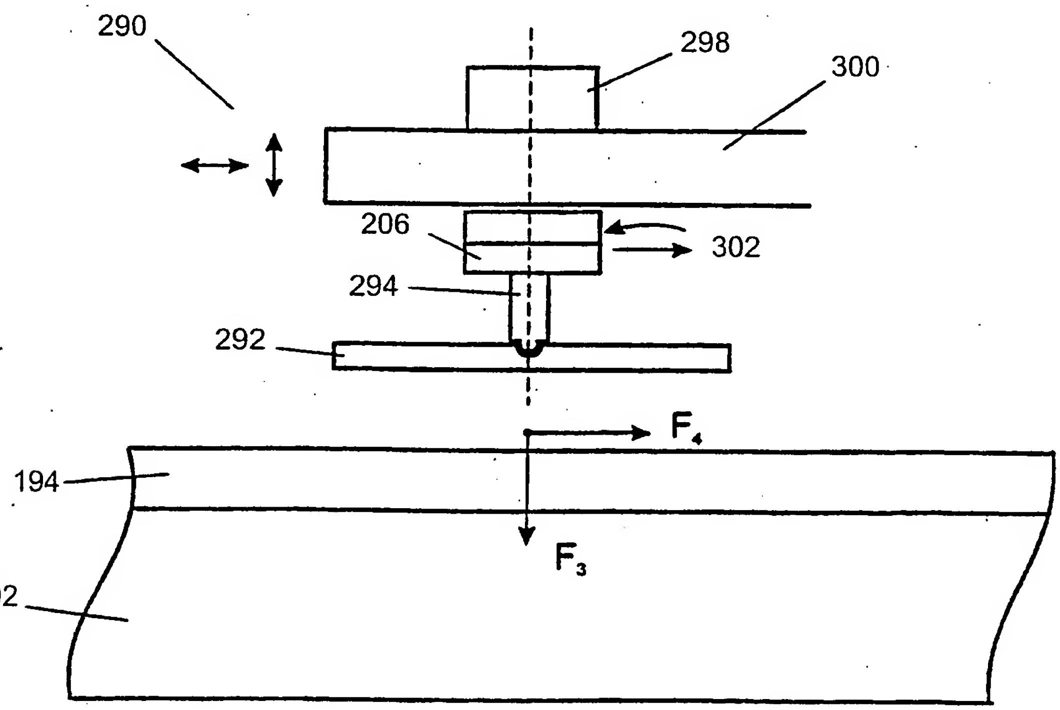
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FIG. 12

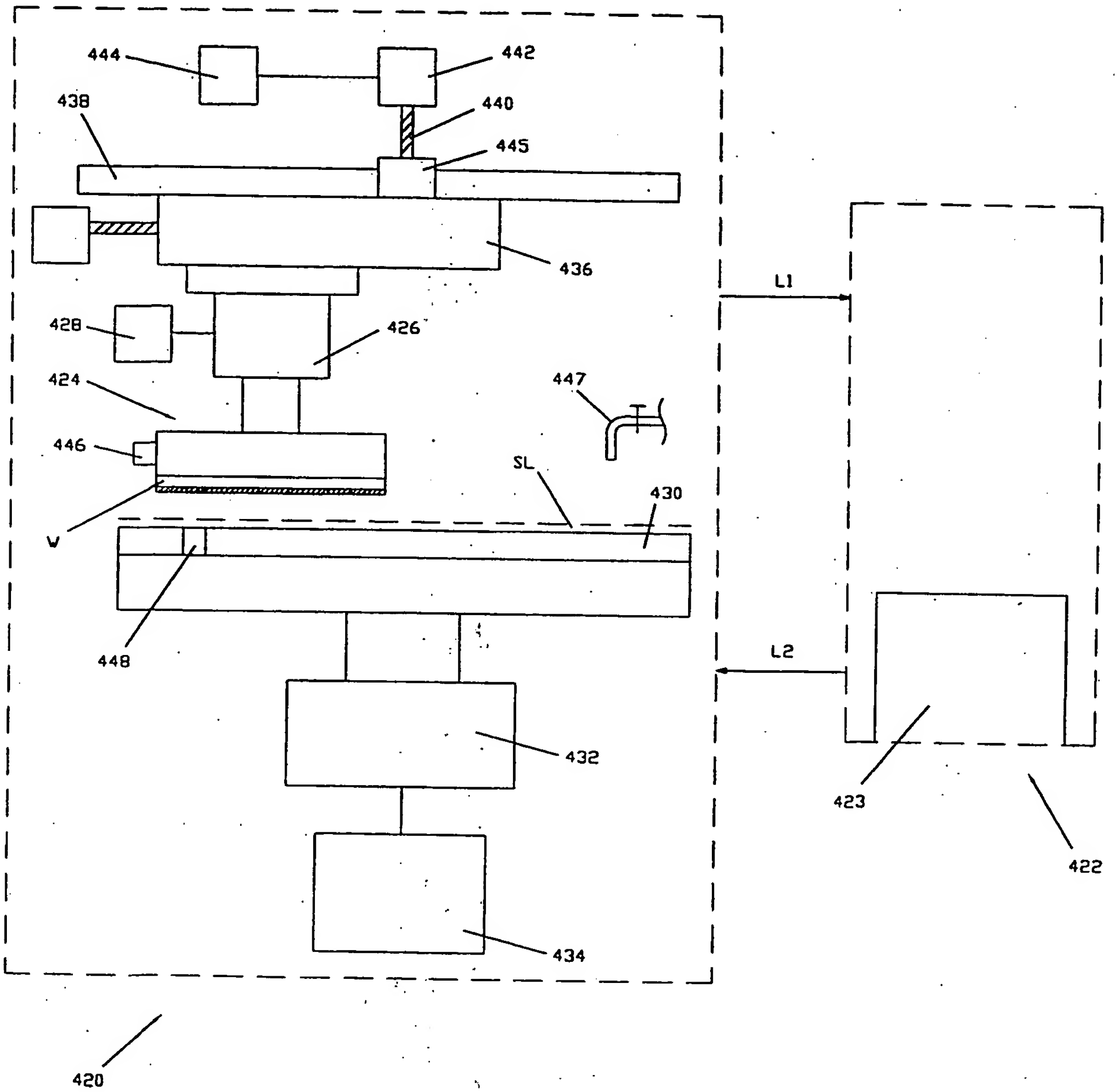
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Fig. 13

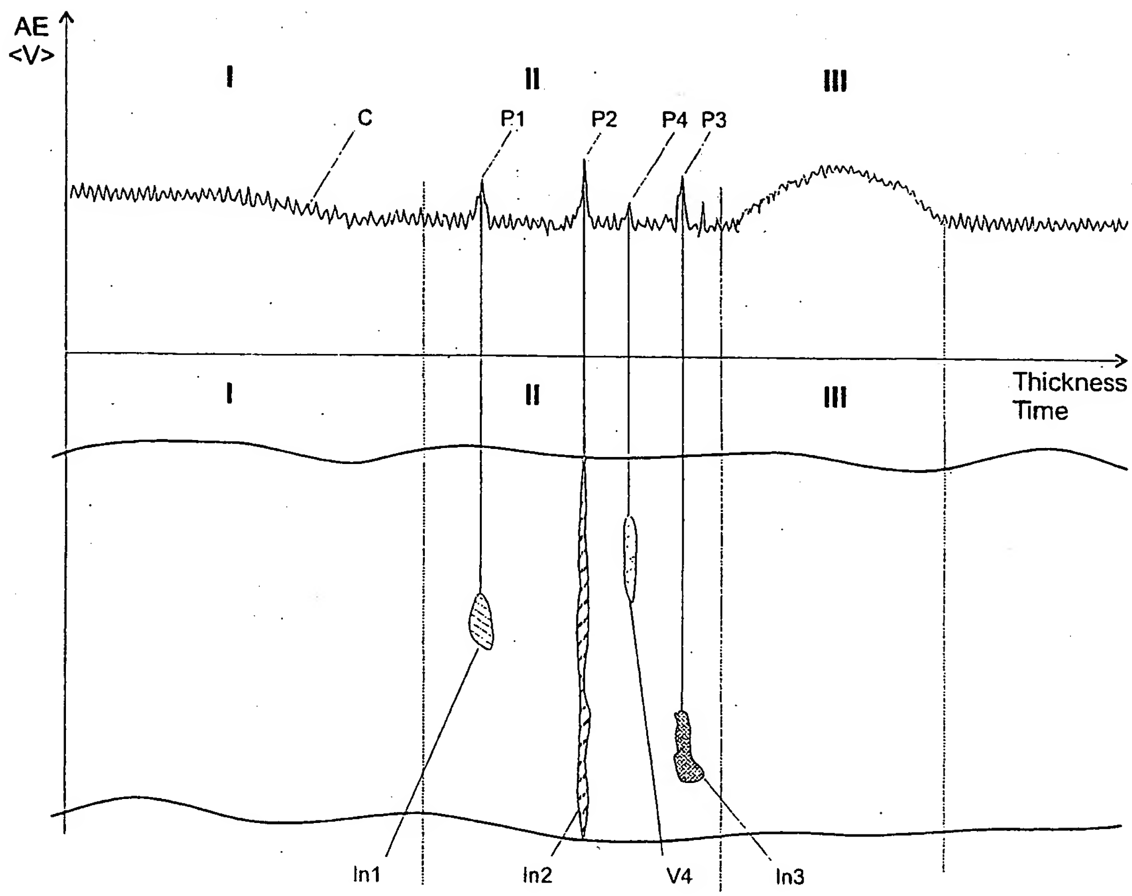


FIG. 14

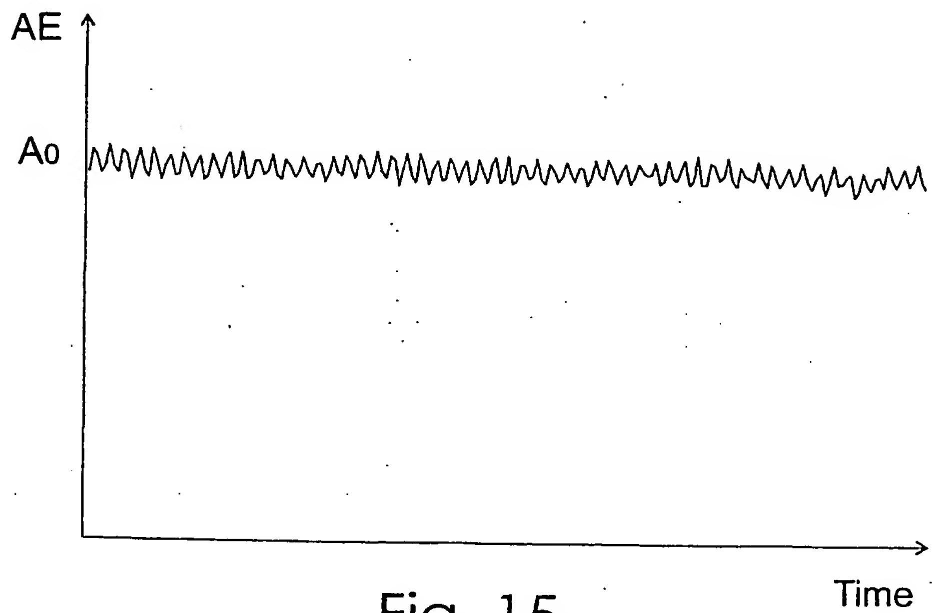


Fig. 15

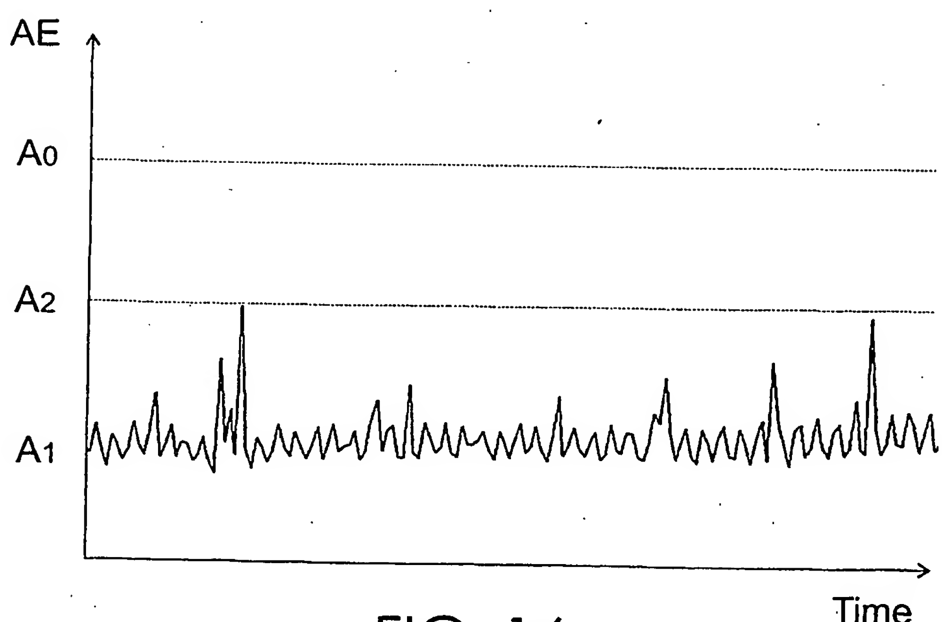
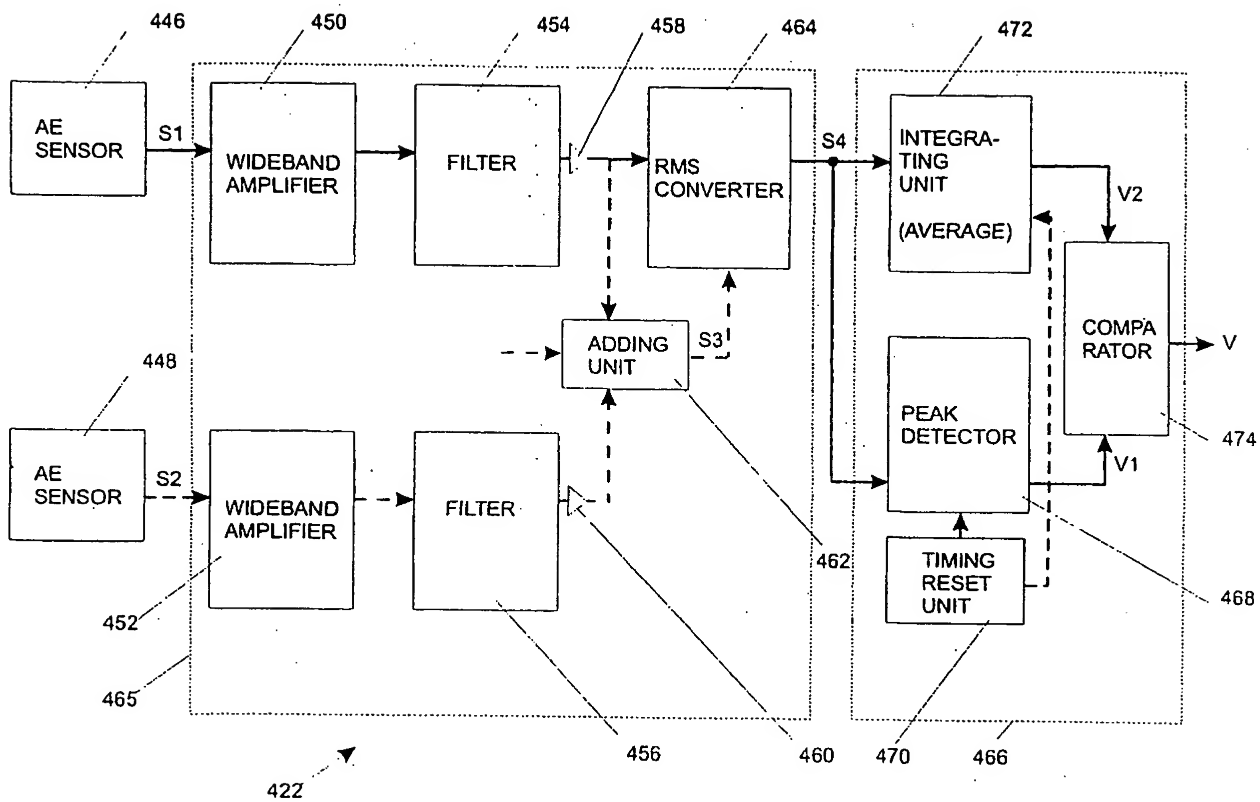


FIG. 16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AE SENSOR
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FIG. 17

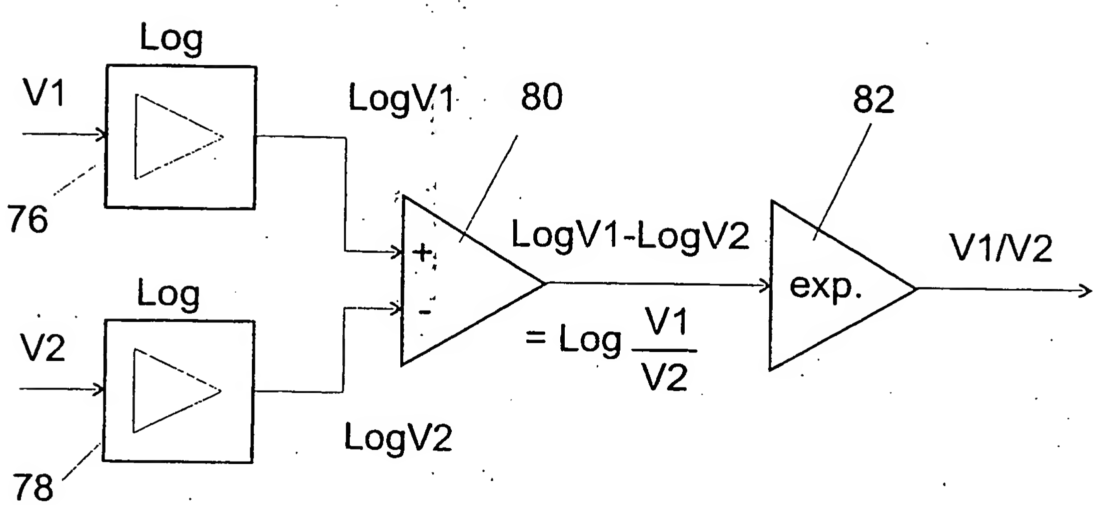
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FIG. 18

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/29755

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :B24B 49/00, 1/00, 29/00
US CL :451/5, 6, 7, 8, 41, 286, 287
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 451/5, 6, 7, 8, 41, 286, 287

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Endpoint detection

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,944,580 A (KIM et al) 31 August 1999	
A	US 6,206,754 B1 (MOORE) 27 March 2001	
A	US 6,352,466 B1 (MOORE) 05 March 2001	

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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Date of the actual completion of the international search
24 MARCH 2002

Date of mailing of the international search report
18 APR 2002

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